Elements of Aeronautics

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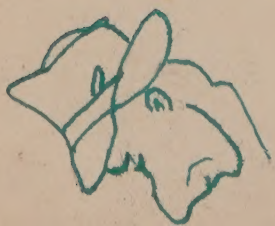

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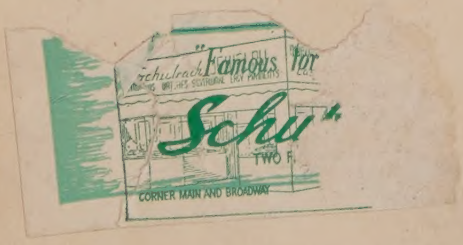

TO YOU WHO STUDY THIS BOOK

THERE are probably several reasons why you have elected to study this book on aeronautics. Certainly you realize that there is now a job ahead for us Americans — an exacting job that calls not only for keen minds and physical fitness, but also for special kinds of training such as this book affords. Those who learn the science and art of flying, as you now propose to do, have unique opportunity to serve our country in this War of Survival that has been forced upon us. In an immediately practical way you are taking up the challenge to freedom. And when our final victory has been won, you will be ready to take your place in an America that has become a nation on wings, honored and respected by all peoples living under a democratic peace.

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Keep 'em Flying

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ELEMENTS OF AERONAUTICS

Part I Learning to Fly
Part II Aerodynamics
Part III Avigation
Part IV Meteorology
Part V Aids and Safeguards

Boeing "flying fortresses" over New York City. *U. S. Army Air Corps*

By FRANCIS POPE, B.A.
First Lieutenant United States Army
Air Corps Reserve
Captain (First Pilot) with Transcontinental
and Western Air, Inc.

ELEMENTS OF AERONAUTICS

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Sciences

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PREFACE

FOR more than a decade there have been scattered efforts to offer instruction in various phases of aeronautics to groups of high school students; and recently the conviction has been rapidly growing among both educators and the non-professional public that high schools generally should be affording young men and women opportunity to obtain basic instruction in the science and art of aviation.

There are two reasons for the concern about this subject. First, the needs of defense have occasioned an intensified general interest in flying, accompanied by an increase in the number of courses in aeronautics offered in the Civil Pilot Training Program and the Army and Navy flying schools. Second, it has come to be recognized that in properly organized courses in aeronautics many of the principles of mathematics, physics, and other sciences now being taught in high schools can be given applications that make those sciences more meaningful and interesting to students than heretofore.

The authors' object in writing this book has been to provide a practical textbook that will make feasible the immediate introduction of a course in aeronautics into any high school. Among the features designed to make the book highly usable as a textbook are the following:

1. *It is comprehensive.* Many books have been written about flying; others have been written about aerodynamics, others about air navigation, still others about meteorology; and some cover the rules and regulations governing flying. But in this book all five of these topics have been treated adequately as phases of the general subject matter.

2. *It is written in language that any high school student can understand.* The authors realize that high school students are not necessarily familiar with algebra, tables of square

roots, and graphic methods, and that quite likely few of them have studied physics. Hence new topics are introduced by easy steps. Every essential matter is so presented from the ground up that any high school student, if reasonably well endowed, can follow the explanations and arrive at a satisfactory understanding of the subject matter.

3. *Practice material is provided.* The book contains a generous amount of exercise material for practice by the students. Throughout the text, wherever exercise material may be profitable, it is supplied. No exercise is presented that has not been preceded by a sample problem completely worked out as a guide. Every chapter is followed by a list of review questions, the answers to which can be found in order in the text of the chapter.

4. *There are adequate aids for the teacher.* The authors have not assumed that teachers will be persons trained in aeronautics; rather, they have assumed the reverse. The *Teacher's Manual* which accompanies the book gives the complete solutions of all exercises. It provides also true-false tests, one for each of the five parts of the book. With the help of the answers included in the Manual, the tests may be scored quickly. At the end of the course they may be given all together as a final examination.

5. *The text prepares the student for the Civil Aeronautics Authority examinations.* The book will give to students a general view of the whole wide field of aviation, with its many opportunities for the employment of diverse abilities. It is not expected to teach anyone actually to fly, even as a book on swimming cannot be expected to teach anyone to swim. However, it is designed to prepare a candidate seeking certification as a private pilot to pass the rigid examinations that he will be required to take in air navigation, meteorology, and the rules and regulations for air traffic laid down by the Civil Aeronautics Authority.

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INTRODUCTION

THERE is no more worthy aviation project than the one undertaken by the co-authors of this book — to lay the early groundwork of air education in the minds of our youth. It should be read by everyone — young or old — who is curious about the machinery and operation of the air world of today and tomorrow. Most adults have been thoroughly impressed, by the frightful lessons of war, with the necessity for building generations of airmen; and the rising generation, which has been sensitized to the importance of air power all along, needs specific information, clearly set forth.

This text — with its interesting and informative presentation — is what has been needed for a long time: aeronautics interpreted not in technical and advanced terms, but in everyday American language used by the man-in-the-street and his son. Many books have been written by fliers on how to fly; but, so far as I know, this is the first complete textbook covering the science as well as the art of flying that has been written in the language of boys and girls in their teens.

I can think of no better combination of authors to produce such a work as this than an experienced educational expert, a man whose interest in aviation is genuine and active, and a transport pilot who can offer direct-from-the-cockpit points of view. Dr. Otis has gained many laurels from his extensive experience and work in the educational field; notable among his contributions is the technique of the United States Army Intelligence Test which was used for examination of all volunteers and recruits entering World War I. As the owner and pilot of his own plane, he is representative of the millions who will soon be in the air "on their own."

Francis Pope is the transport pilot. A graduate of Stanford University, he came into commercial aviation by way of the Army Air Corps and has been flying for Transcontinental and Western Air since 1935. He is representative of the vanguard that has explored and charted the new realm of air transportation. Our airline pilots are of the very highest type of American manhood. I often think of them as they fly overhead, hidden by clouds, storms, fog, and snow, guiding tons of material on aerial highways by electrical signals, which they interpret into exact direction and miles made good on an airline schedule. These young men have brought us the air age.

I heartily recommend this book for the valuable and practical information it holds for our enterprising young people. Those who aspire to a part in the new air age, with that thirst for knowledge and the spirit of gay conquest so typically American, will find this book a clear and true beacon.

AL WILLIAMS

PART I

Learning to Fly

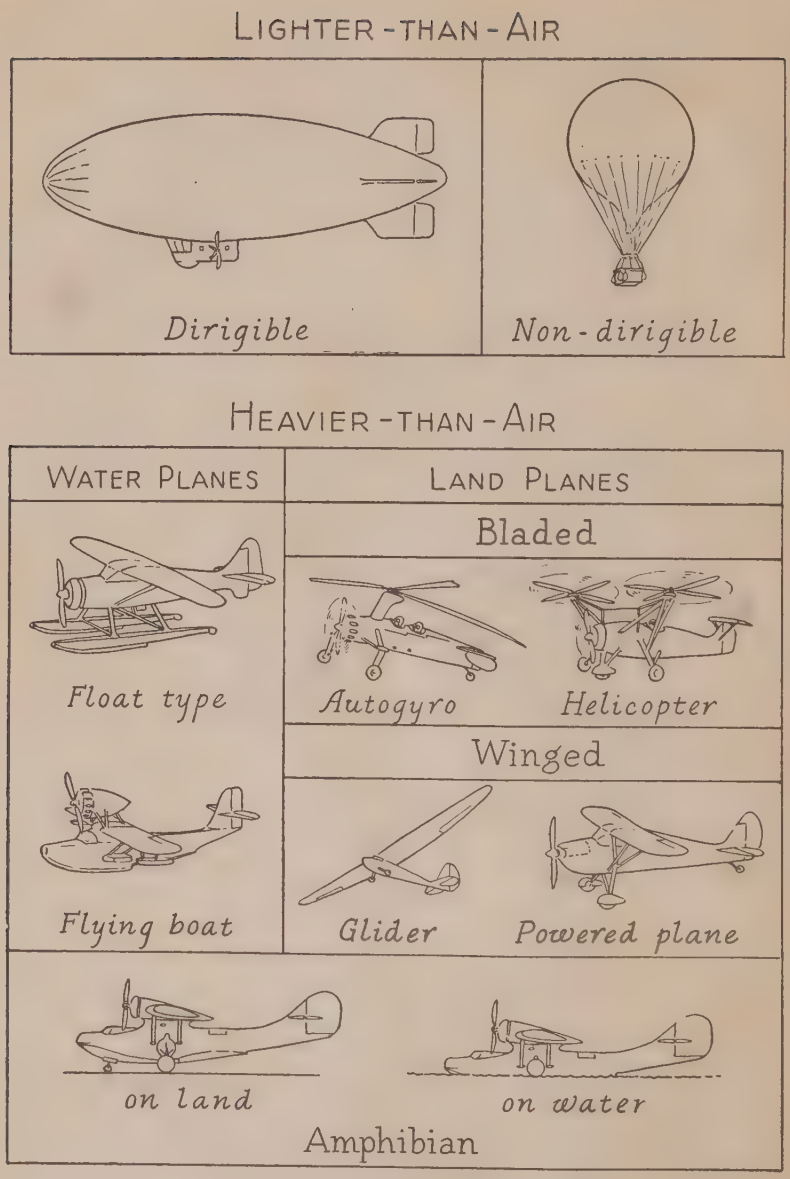


FIG. 1. The various forms of aircraft.

1

HOW AN AIRPLANE FLIES

THE term *aircraft* applies to any and all vehicles of the air. Aircraft may be divided into two main classes: lighter-than-air and heavier-than-air. The lighter-than-air craft, those whose weight is supported by buoyancy, are in in two subclasses: dirigible (steerable), such as airships or blimps, and non-dirigible, such as balloons. (See Fig. 1.)

Heavier-than-air craft whose weight is supported dynamically, as explained later, may be divided into three general classes: water planes, land planes, and amphibian planes. Amphibian planes are capable of taking off from and landing on either water or land.

Some water planes have floats; others are flying boats.

Heavier-than-air craft may be divided also into two general classes which we might call *bladed* and *winged*. Some bladed planes have small wings, however. Bladed planes are called autogiros, or helicopters, and are supported principally by rotors of three or four blades. Bladed planes are sometimes called *rotary-wing* planes.

Winged planes may be subdivided into gliders and powered planes, depending upon whether the plane has an engine.

Winged planes may have one wing (monoplane) or two wings (biplane) or three wings (triplane). Having "one wing" means having one wing on each side.

Powered craft are single-engined or multi-engined.

A parachute (shown on page 595) may be thought of as a special, slightly dirigible, heavier-than-air craft.

This book deals principally with single-engined winged land planes.

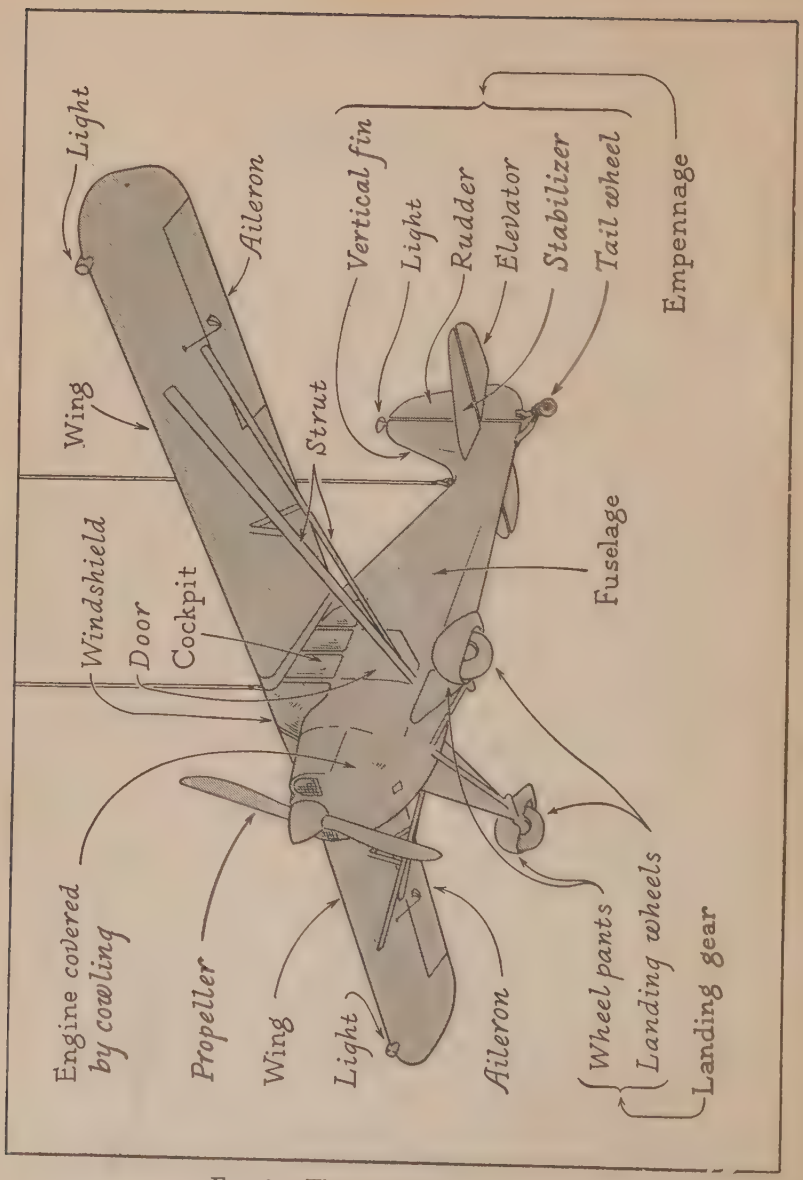


FIG. 2. The parts of an airplane.

Parts of a plane

The principal parts of a plane are:

the fuselage (or body),
the wings,
the engine,
the propeller,
the landing gear (landing wheels and supports), and
the empennage (tail surfaces).

Figure 2 shows these and names various special structures which we must frequently discuss. You will learn these gradually as we refer to them in the book.

What makes an airplane fly?

You doubtless feel satisfied that you know what makes an airplane go forward — how the propeller, pushing backward on the air, pulls the plane forward. It is the same as the propeller of a steamship or motorboat pushing backward on the water and thereby pushing the boat forward. You may wonder, however, what holds the plane up in the air.

A full explanation of what holds a plane up is quite technical and would be out of place at this point.

We give you here a very simple explanation. Later the matter is treated more fully.

Skiing on the water

Perhaps you have seen pictures of the new sport of skiing on the water behind a motorboat, as shown in Figure 3. You

FIG. 3.

put on ordinary skis and hang on to a rope that is pulled by a fast boat. (Earlier a single board called an "aquaplane" was used.) The skis are always pointing slightly upward, as shown at the left in Figure 4, and the water strikes the underside of the skis at such a rapid rate that its force is sufficient to sustain the weight of a person.

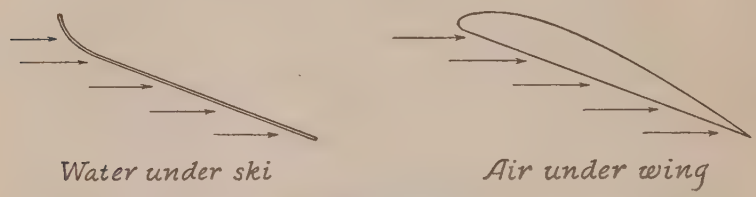


FIG. 4. An object may be lifted by the slanting force of a fluid on its under surface.

Rapidly moving plane

A plane is held up in somewhat the same manner as the person skiing on the water. That is, the wings of a plane are set at a slight slant, as shown in Figure 5, which is the side view of a plane, looking at the wing from its end.

In flight the air strikes the underside of the wings with such force as to create a lift sufficient to hold up the weight of the plane. The propeller which bites into the air and pulls the plane is like the rope from the motorboat pulling the skier.

Flying speed

As you can easily imagine, if the motorboat towing a skier slows down, the skier promptly sinks into the water. And similarly, if a plane is not propelled rapidly enough, it has not enough lift to fly. The necessary speed of forward motion to enable a plane to fly is called its *flying speed.*

It is possible to get lift without having the wings slant as shown in Figure 5, but the explanation requires a study of *airfoils* and *streamlines* and is reserved for a later chapter.

Stalling

When a plane slows its forward motion sufficiently to lose flying speed, it *stalls;* that is, it begins to fall to the ground, just as a kite would fall to the ground if the wind stopped blowing or just as the skier promptly sinks when not pulled forward rapidly enough.

Questions

1. Into what classes may aircraft be divided?
2. How many parts of a plane can you name? What are they?
3. What is the empennage?
4. What similarity is there between the wings of an airplane in flight and a kite?
5. What happens when a person skiing on the water lets go of the rope?

Fig. 5. An airplane with its wing at a slight angle to its longitudinal axis.

2

MOTIONS OF A PLANE

IN addition to going straight ahead, a plane can make three fundamental motions, which are called *yawing*, *pitching*, and *rolling*.

Yawing refers to the turning of a plane to the right or the left as a bicycle is turned by the handle bars or a ship by the rudder. Yawing is done usually by the feet on pedals.

Yawing is sometimes spoken of technically as *rotation about the normal axis*. (See Fig. 6.) In straight and level flight the normal axis is the vertical line through the center of the weight of the plane.

Pitching refers to the up or down motion of the nose of the plane, which makes it go "uphill" or "downhill," as we might say.

Pitching is sometimes spoken of technically as *rotation about the lateral axis*. The lateral axis of a plane in straight

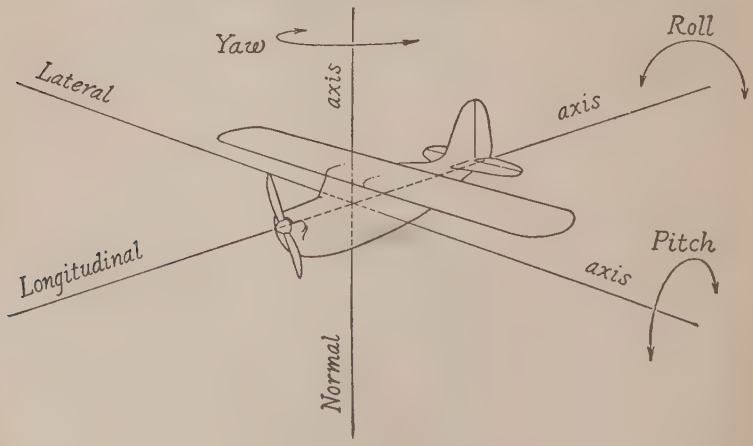


FIG. 6. The axes of a plane.

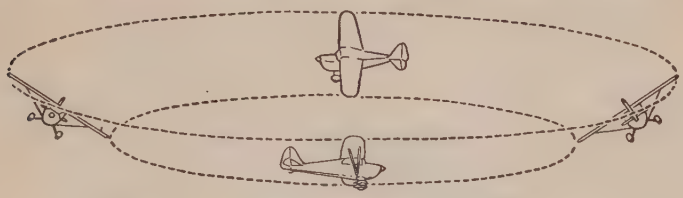


FIG. 7. A plane as it is banked in a turn.

and level flight is horizontal and crosswise of the plane. Technically it is defined as the line through the center of gravity perpendicular to the *plane of symmetry*. As a plane rests on the ground, the plane of symmetry is, of course, the vertical plane through the middle of the airplane dividing it into symmetrical halves.

Rolling refers to the lifting of one wing and lowering of the other in flight. Rolling is technically spoken of as *rotation about the longitudinal axis*. The longitudinal axis may be defined as the line through the center of gravity parallel to the propeller shaft.

Actually, of course, each of the motions of rotation mentioned above is combined with the motion of *translation* — that is, with forward motion.

Banking

When a plane has rolled from a position with wings level into a position with one wing raised and one lowered, it is said to be *banked*. A plane is banked while making a normal turn (Fig. 7), just as the roadbed of a railroad is banked on a turn by having the outer rail placed higher than the inner one. A plane *rolls* into or out of a banked position.

How to yaw a plane

A plane is yawed (steered) by means of a rudder moved by the feet pushing against pedals, as shown in Figure 8. The motion of the pedals is transmitted to the rudder by means of cables, as shown.

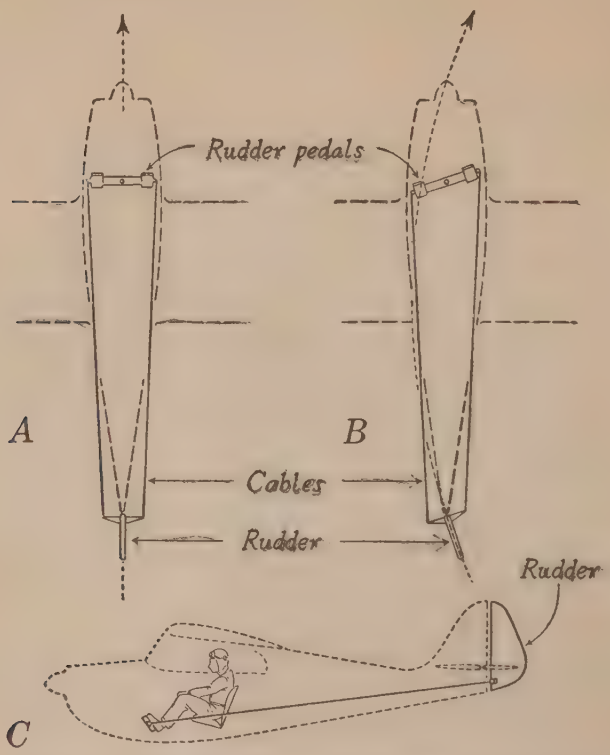


FIG. 8. A plane being yawed by means of the rudder moved by the rudder pedals.

When the right foot is pushed forward, as shown at *B* in the figure, the right pedal going forward pulls the rudder to the right. This makes the rear of the plane move to the left, because of the greater pressure of air on the right side of the rudder. The plane therefore turns to the right. So we have "right foot — right turn" and "left foot — left turn."[1]

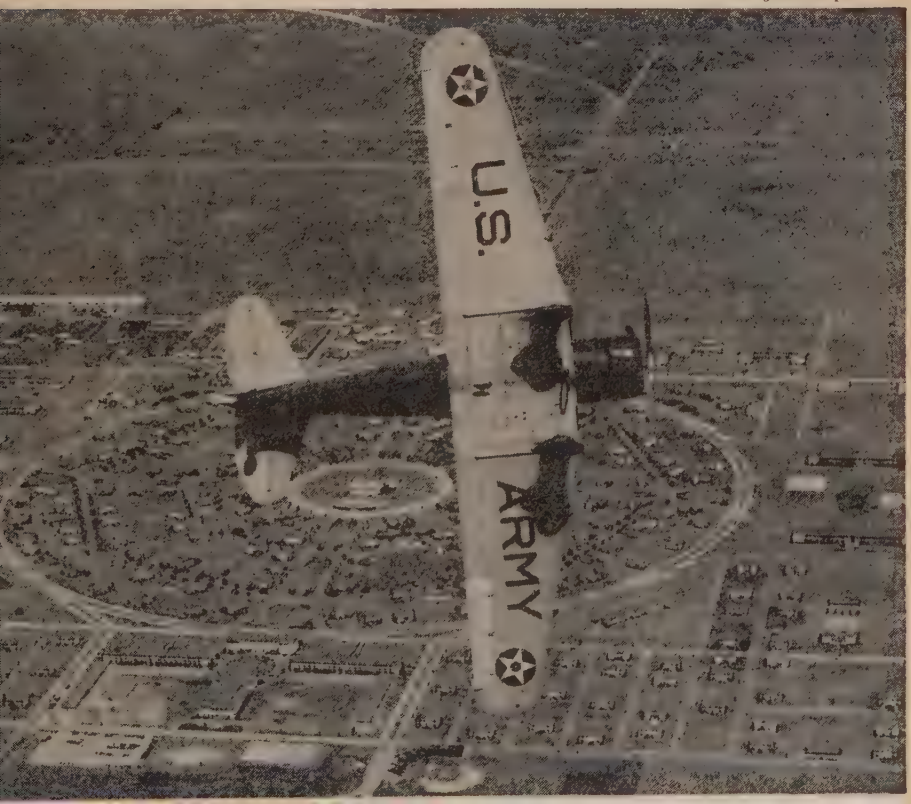
[1] The method of yawing a plane is considered by many to be an unfortunate arrangement because of being unnatural. That is, if you wish to steer a bicycle to the *right*, you push forward on the *left* handle bar. If you wish to turn an auto to the *right*, you push forward on the *left* side of the steering wheel. If you wish a sled to turn to the *right*, you push with your *left* foot. Flying a plane of the present type therefore requires the learning of a new steering habit, which is the reverse of the natural one.

You must understand that in yawing a plane, a forward *position* of the foot pedal produces a yaw (turn) of the plane. The farther forward the foot pedal is, the faster the plane yaws, just as the farther you turn the wheel of an automobile the faster the car yaws. The longer you hold the pedal forward, the longer the plane will continue to yaw.

During the time that the right pedal is being brought back to the neutral position (by a push of the left foot on the left pedal), the yawing is slowing down. The yawing stops only when the pedals are completely back to neutral. Therefore, if you are going north and wish to go east and you keep the

FIG. 9. A North American basic training plane in a very steep bank, a position that can be maintained only momentarily without loss of altitude. The plane is shown over Randolph Field, Texas, with the Air Corps Basic Flying School in view.

U. S. Army Air Corps



right pedal forward until the plane points east, you will find that by the time you have returned the pedals to neutral the plane has turned past east. Even if you could return the pedals to neutral instantly on reaching east, thereby straightening the rudder instantly, the plane would still yaw a little past east because of its turning momentum. The air cannot stop the yawing of a plane instantly. This is why you must begin to return the pedals to neutral *before* you have quite yawed to the east. What you should try to do is to get the pedals back to the neutral position just at the instant the plane points east.

Remember:

A forward *position* of the right foot pedal means a continuous *yawing* to the right.

A forward *position* of the left foot pedal means a continuous *yawing* to the left.

Neutral *position* of the feet (side by side) means *no yawing*. It means continuous motion in a straight line.

The farther forward the pedal, the faster the yawing.

The pedals must be completely back to neutral at the finish of the yaw.

How to pitch a plane

Pitching a plane means pointing its nose up or down.

A plane is provided with a *stick* (or its equivalent) which as originally designed came up from the floor of the plane between the pilot's knees, as shown in Figure 10. More recently the "stick" is often a curved bar which allows more leg room.

To point the nose of the plane up, you pull the top of the stick back toward you, just as you would pull back on the handle of a pitcher to make the spout turn up.

To point the nose down, you push forward on the stick.

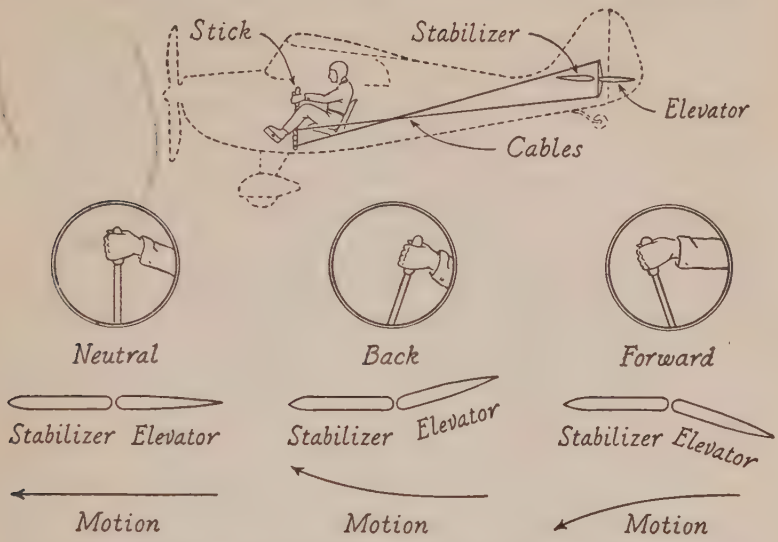


FIG. 10. The procedure in pitching a plane by means of the elevator moved by the stick.

The movement of the stick is transmitted by cables to the elevator in such a way that as you pull back on the stick, the elevator, which is hinged at its front edge, is pointed upward in the rear. Note how the cables are crossed. The extra pressure downward on the upper side of the elevator pushes the tail down, thereby causing the nose to point up. Pushing the stick forward pushes the elevator down, causing the tail to be pushed up and the nose pointed down.

In either case, the movement is a natural one.

You should understand that for a given distance the stick is pulled back there is a given amount of turn upward. The farther back the stick is pulled, the more sharply the plane turns upward. The longer you hold the stick back, the longer the plane will turn its nose upward, until if you are going fast enough you loop-the-loop.

If you want the plane to climb, you hold the stick back

until the nose has risen to just the desired angle (or nearly so); then you move the stick back to neutral (where it was at first). During the time the stick is being returned to the neutral position, the upward turning is slowing down, and it stops just at the instant the stick reaches neutral. That is why you do not hold the stick back until the full desired climbing angle is reached. If you did, then during the time the stick was being returned to the neutral position the nose of the plane would still rise a little and finally be too high. Actually, therefore, you begin to return the stick to neutral just before reaching the desired climbing angle, so that the desired climbing angle will be reached just as the stick reaches neutral.

This same principle applies to the case in which you wish to point the nose down. That is, if you want to descend, you push the stick forward, producing a downward turn, and you keep the stick forward till the plane points nearly as far down as you wish. Then you return the stick to neutral and the plane continues to point in the same downward direction.

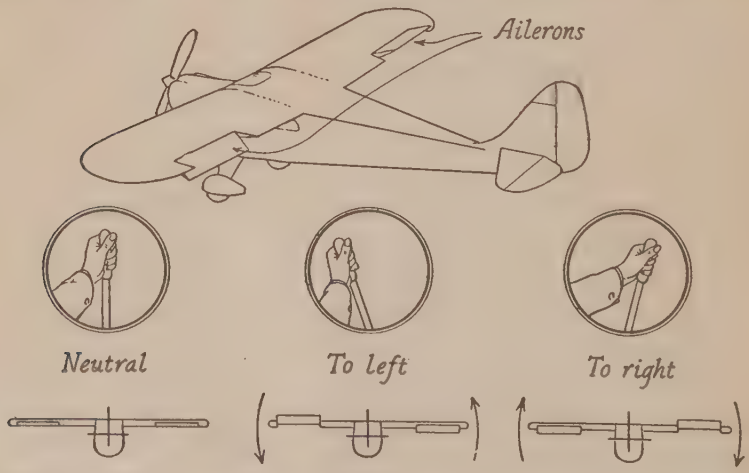


FIG. 11. The procedure in rolling a plane by means of the ailerons moved by the stick.

When ready to level off you pull the stick back and hold it till the plane is about to become level; then you return the stick to neutral again.

Remember:

Backward *position* of the stick means upward *turning* of the nose of the plane.

Forward *position* of the stick means downward *turning* of the nose of the plane.

Neutral *position* of the stick means *no turning* up or down. It means level flight or steady climb or steady descent.

The farther the stick is away from neutral, the faster the turning up or down.

The stick must be brought back completely to neutral by the time the desired amount of upward or downward turn is reached.

How to roll a plane into or out of a bank

If you want to roll a plane to the right (lower the right wing as is done when turning to the right), you push the stick to the right (a natural movement); and if you want to roll the plane to the left, you push the stick to the left.

The motion of the stick is transmitted by cables to the two *ailerons* (Fig. 11), one on each wing, each aileron being a small movable portion of the back edge of the wing. When you push the stick to the right, the right aileron is lifted and the left aileron is lowered. Air flowing over the wings pushes the right wing down and the left wing up. This rolls the plane to the right.

Pushing the stick to the left produces the opposite motion in both ailerons and rolls the plane to the left.

You should understand that if you wish to roll the plane to the right to bank it at an angle of 45°, you do not push the stick over to 45°. A slight position of the stick to the right of vertical causes the plane to start to roll and to keep on rolling more and more until the desired amount of bank is reached.

If you hold the stick to the right, the plane will keep on rolling till it is straight up on edge, so to speak; and if you are going fast enough and hold the nose up, the plane will keep on rolling till it is over on its back and then will come up on the other side; it will roll over and over.[1] If you bring the stick back to neutral (perpendicular to the bottom of the plane) when the plane has rolled to the desired angle, it tends to remain banked at that angle.

To level a plane that is banked to the right, you move the stick to the left and hold it there until the plane rolls leftward back to level, then move the stick back to neutral.

Actually if you wish to bank a plane to an angle of 45°, you do not hold the stick to one side until the 45° angle is reached, because during the time the stick is being brought back to neutral, the turning of the plane on the longitudinal (lengthwise) axis is merely being slowed down to zero. Therefore, during this time the plane will have rolled slightly past 45°. What you do, therefore, is to begin to return the stick to neutral when about to reach 45° and try to get the stick back to exactly neutral at the instant the plane reaches the 45-degree bank.

Remember:

A right *position* of the stick means a *roll* to the right.

A left *position* of the stick means a *roll* to the left (this may be a roll back to level from a bank to the right).

Neutral *position* of the stick means *no roll*. It means continuous level flight (so far as banking is concerned) or a fixed amount of bank to one side or the other.

The farther away from neutral the stick is, the faster the roll.

The stick must be brought completely back to neutral at the instant the desired angle of bank is reached.

[1] There is a maneuver called the *normal roll* produced in this way which is useful as a military maneuver but is completely useless in all other flying.

Control movements become automatic

The student will need to give careful attention at first to the control movements of rudder and stick; but gradually these movements become automatic, and in a short time the student has merely to think, "I want to lift the nose," and he automatically pulls back on the stick in the proper manner; or he has merely to think, "I want to tip the plane to the left" (roll it into a left bank), and he automatically moves the stick to the left and holds it there until the desired degree of bank is about to be reached and then returns the stick to neutral. The early practice in flying consists largely in making these reactions automatic.

Counterbalancing control surfaces

In some planes a portion of the rudder projects forward from the hinge, as shown at *A* in Figure 12. This makes the rudder easier to operate. Pressure of air on part *B* of the rudder, turned as shown at the right in Figure 12, tends strongly to straighten the rudder, and it requires a good deal of foot pressure to hold the rudder in the turned position. You can see that with the rudder so turned there is pressure of air against part *A* on the same side; but this force tends to turn the rudder in the *opposite* direction, counteracting part

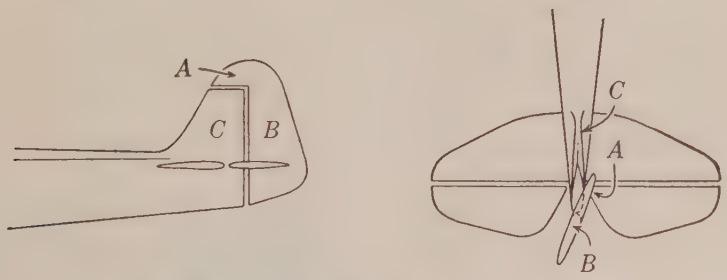
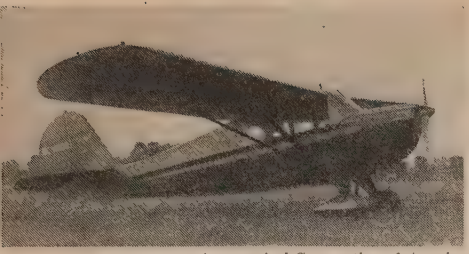


FIG. 12. Side view (left) and top view (right) of a counterbalanced rudder.



Aeronautical Corporation of America

FIG. 13. The Aeronca shown here and the Piper Cub (Fig. 14) are popular light planes of conventional type, both of which are widely used by private pilots. They are also much employed as training planes.

of the force on part *B*. These counteracting forces require no foot pressure, but both of them help to yaw the plane. In the figure both these forces are tending to push the tail of the plane to the right and in that way to turn its nose to the left. It is possible to counterbalance other control surfaces, such as an aileron or elevator, in the same way.

Dep control

Many planes are equipped with a wheel in front of the pilot to take the place of the stick, as shown in Figure 15. The plane of the wheel is vertical, and the wheel is mounted on an axle extending directly forward. In such a plane, instead of pushing the stick to the right or left, you turn the wheel to the right or left. Instead of pulling the stick back toward you, you pull the wheel toward you, sliding its axle. Instead of pushing the stick forward toward the nose of the plane, you push the wheel forward.

The stick control was devised by a man named Joyce, and the stick has come to be called a "joy stick" (Joyce stick). The wheel is called a Deperdussin control or merely a "dep control." The dep control is used universally on planes of large gross weight; the stick control is used on planes of comparatively low gross weight that require high maneuverability.

Piper Aircraft Corporation

FIG. 14. The Piper Cub.

Questions

1. What are the three principal motions (rotations) a plane can make?
2. What are the control surfaces of a plane?
3. What control surfaces are used for each motion of the plane?
4. How does the pilot move these control surfaces?
5. What vehicles besides airplanes are usually banked on a turn?
6. Is it motion or position of the pedals that causes the plane to yaw? Explain.
7. Is a plane steered like a bobsled?
8. How is a rudder counterbalanced?
9. Yawing is rotation on what axis?
10. Pitching is rotation on what axis?
11. Banking is rotation on what axis?
12. To lift the nose of a plane, what control motion is made?
13. To lift the right wing, what control motion is made?
14. To move the nose to the left, what control motion is made?
15. If a plane is banked to the left, how do you bring it back to level?
16. What is a dep control?

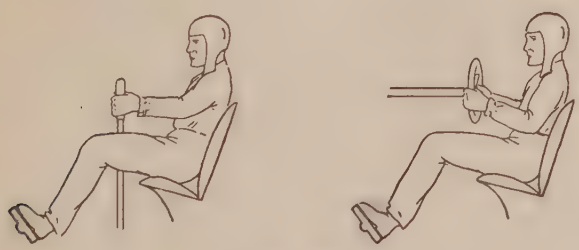


Fig. 15.

3

BANKING, SKIDDING, AND SLIPPING

FLYING a plane may be compared with driving an automobile on a very slippery pavement. For example, if you are driving a car northward on an icy boulevard at a fairly rapid rate and attempt to make a turn to the right, you may find that you are able to make the car face slightly to the east of north, but it may continue to move toward the north; that is, it will skid sideways toward the left.

Similarly, if you are flying a plane toward the north with the wings level, and attempt to make a sharp turn to the right by yawing only, the plane will point slightly toward the east, but will continue to move northward as shown at (*a*) in Figure 16. In other words, the plane also will *skid* to the left.

Again, if you were to attempt to drive a car on a straight highway which slanted off to the right rather steeply, you would find on an icy day that the car had a tendency to slip sidewise toward the right, and similarly if you were to attempt to fly a plane in a straight line toward the north, with the plane banked so that the right wing was down, you would find that the plane slipped sideways toward the right, as shown at (*b*) in Figure 16. It would continue to point north, but its actual motion would be a little to the east of north and a little downward. In that case we say that the plane is *slipping* to the right.

Banking the plane in a turn

If you were to attempt to drive a car at a fairly rapid rate on a curved highway which is icy, you would find, if the highway were level, that the car had a tendency to skid,

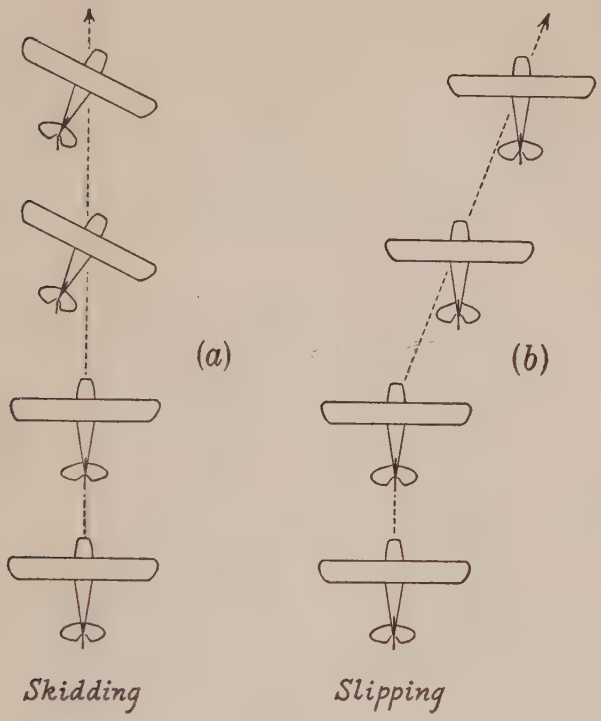


FIG. 16.

whereas if the highway is *banked* (sloped toward the inside of the curve), you would find that at the proper rate of speed the car would make the curve without either skidding or slipping. If the angle of bank is insufficient for your rate of speed and the radius of turn, you may skid over the edge of the highway, and if the angle of bank is too great, the car may slip toward the inside of the curve.

Similarly, in flying a plane there is a certain degree of banking necessary for a turn of a given radius at a given rate of speed, and if the plane is banked at this proper angle, it will neither skid nor slip. If the banking is insufficient for such a turn, the plane will skid, and if the banking is too great, the plane will slip toward the inside of the curve.

How to judge the right amount of bank

When the angle of banking is insufficient for the radius of the curve attempted and for the rate of speed of the plane, and the plane is therefore skidding away from the center of the curve, the pilot has the feeling of being thrown against the side of the plane away from the center of the curve. In that case, of course, the pilot should increase the angle of bank.

On the other hand, if the angle of bank is too steep and the plane is therefore slipping toward the inside of the turn, the pilot will feel himself thrown toward the side of the plane on the inside of the curve. In that case, of course, he should decrease the angle of bank.

When, in a banked turn, the pilot has a feeling as if he were sitting directly upright in the plane (no tendency to be swayed either to the right or the left), he knows he has approximately the right angle of banking for the turn he is attempting. This is called "flying by the seat of the pants."

This fact has its disadvantages also. If a pilot has to fly in weather with visibility so poor that he cannot see the ground or the horizon, he cannot tell by the feeling of his

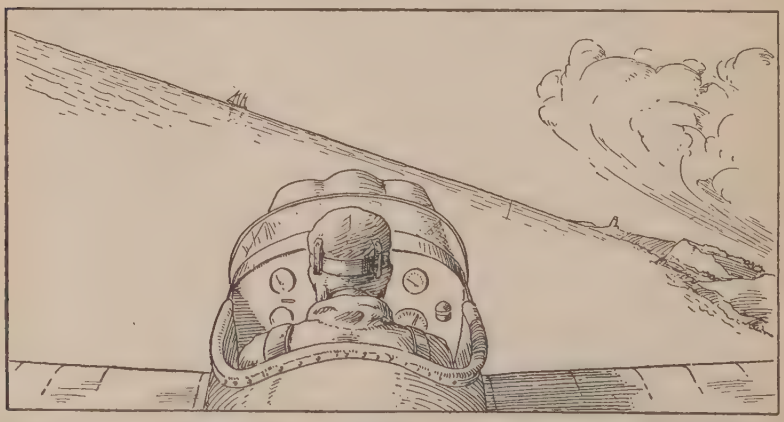


FIG. 17. The horizon as seen, apparently tipped, from a plane in a banked turn.

plane whether he is flying level or turning to the right or the left with a proper amount of banking. Many times a pilot has thought he was flying level and straight when actually he was going around in a circle or even diving downward. That is one reason that pilots have been injured trying to fly in poor visibility, and that it is necessary to have additional instruments in order to "fly blind."

The horizon tips

An interesting fact which one who has not flown might not expect is that in making a turn one very frequently has the feeling that the plane is remaining level and the horizon is tipping up, as shown in Figure 17. Thus, if you turn to the left with the proper amount of bank, your sensation is the same as if you sat vertically in a level plane. This makes the plane seem level, and the horizon seems tipped up at the left and down at the right, as shown in the figure. The steeper the bank, the steeper the appearance of the horizon.

Banking, yawing, and pitching required in a turn

If you were to attempt to drive an automobile around a saucer-shaped race track, even though the track were banked at a steep angle, you would find it necessary to turn the wheels slightly toward the inside of the track in order to stay on it. Similarly in flying, even though the plane is steeply banked to make a turn, it is necessary to yaw the plane somewhat in the direction toward which you wish to turn. Otherwise the plane will slip toward the side of the lower wing.

Also in driving around the saucer-shaped race track you will find, especially if the track is very steeply banked, that from the driver's point of view the front of the car is rising; that is, it is pitching upward slightly. You would realize this because you would get the same sensation as when you

dip and rise rapidly in a roller coaster. Similarly, in flying a horizontal curve, the plane is continually pitching upward slightly. If the plane is merely banked and yawed and not pitched, it will merely curve off sideward and downward into a dive.

Thus we see that in order to fly a normal turn (a level arc of a circle), it is necessary properly to coördinate the three motions — bank, yaw, and pitch.

Making a normal turn

As you have just seen, to make a normal turn you must roll, yaw, and pitch the plane. An experienced pilot does all these at the same time. However, a beginner may do them in succession if desired. For example, to make a normal turn of moderate radius, to the right, let us say, you may begin by rolling the plane into a moderate right bank by pushing the stick to the right a moment, then back to neutral; thereupon promptly give the plane a slight yaw to the right (right foot held forward); next give the plane a slight pitch upward (stick held slightly back). If the amounts of banking, yaw, and pitch are proper in relation to one another, the plane remains at a constant degree of bank and flies in a circle at a constant altitude without slip or skid; that is, it makes a *normal turn.*

To come out of a turn and go straight ahead, you must stop yawing and pitching and restore the plane to the level position of the wings.

To do this by steps, you might first stop the pitch (releasing pressure on the stick and letting it go back to neutral); next stop the yaw (release pressure on the right pedal and let the rudder go back to neutral); then roll the plane back to level (move the stick to the left a moment, then back to neutral). You may execute these control movements thus by steps in order to learn what each control movement contributes to the maneuver; but you must understand that in good flying

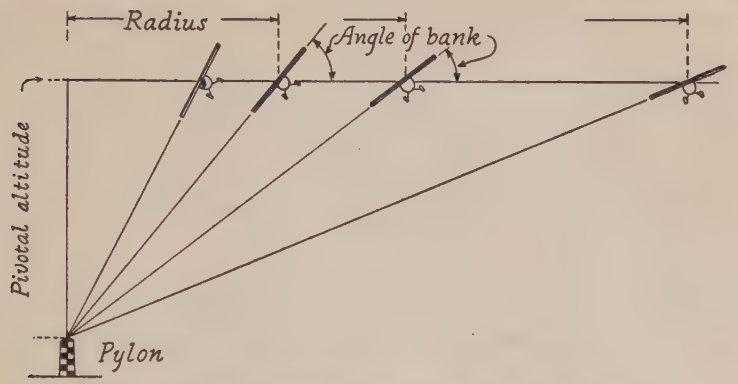


FIG. 18. The pivotal altitude for an on-pylon turn.

the three movements must be made together and properly coördinated. Coördination is the soul of flying.

Pivotal altitude

For any given speed there is a certain altitude above ground at which a plane can fly in a circle around a pylon (or point on the ground) at the proper degree of bank with the lateral axis pointing directly toward the pylon at all times. This particular altitude is called the *pivotal altitude* for that particular speed.

The pivotal altitude is the same no matter what the radius of turn, as shown in Figure 18. The greater the radius the less the necessary bank, but at the pivotal altitude the lateral axis can always point directly toward the pylon.

The pivotal altitude for a speed of 100 miles an hour is 670 feet, and for a speed of 200 miles an hour it is 2680 feet. The pivotal altitude varies as the square of the speed; that is, if you double the speed, the pivotal altitude is multiplied by four.[1]

[1] The formula for finding the pivotal altitude is $P.A. = .067\ A^2$, in which $P.A.$ is the pivotal altitude in feet and A is the speed of the plane in miles per hour. The derivation of this formula is given in Chapter 18.

Relation of bank, yaw, and pitch to one another in a turn

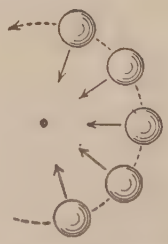
In a normal turn at a 45-degree bank the amount of yawing necessary and the amount of pitching necessary are equal. However, since yawing is done with the feet on the foot pedals and pitching is done with the hand on the stick, you will not be able to perceive that the amounts of yaw and pitch are equal.

As the radius is increased and the angle of bank consequently decreased, less yaw and pitch are needed; but the amount of pitch necessary decreases more rapidly than the amount of yaw necessary, so that for a large circle only a small amount of yaw is needed and practically no pitch. On the other hand, as the radius decreases and the angle of bank consequently increases, more yaw and pitch are needed; but the amount of pitch necessary increases more rapidly than the amount of yaw necessary, so that for a very steep angle of bank somewhat more yaw is needed than for a moderate bank, while several times as much pitch is needed as for a moderate bank.

A better understanding of banking in a turn

One of the fundamental laws of motion is that a body in motion tends to continue to move in a straight line. In order to make it move in a curved path, force is required to act on the body continuously.

No force needed



Force needed toward center of curve

Fig. 19.

A ball such as a bowling ball once started will roll in a straight line without any force acting on it. But to make a ball move along the arc of a circle, as shown in Figure 19, a "sideward-inward" force must continually act upon it. We say *sideward* because the force must be perpendicular to the path of motion, and *inward* because the direction of the force must change with the changing direction of the body to be always in the direction of the center of the path of motion. A sideward-inward force of this sort which always acts toward a center is called a *centripetal* force. ("Centripetal" means moving toward a center.)

FIG. 20.

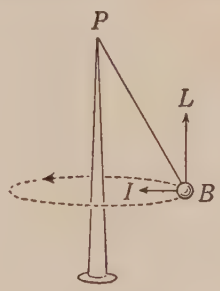


FIG. 21.

If the weight of a ball is supported on a level surface, the centripetal force necessary to make it travel in a circle may be the continuous pull of a string with one end fastened to a point in the center of the circle, as shown in Figure 20. The centripetal force of the string on the ball in Figure 20 necessary to cause the ball to move in a circle is opposite and just equal to the *centrifugal* force of the ball on the string caused by the tendency of the ball to travel in a straight line. ("Centrifugal" means moving away from a center.)

A ball may be supported and also pulled in the direction of the center of a circle by the same string, as shown in Figure 21. Here a ball, *B*, is fastened to one end of a string, the other end of which is fastened to the top of a pole, *P*. If given a proper starting push, the ball will swing in a circle around the pole.

While the actual pull of the string on the ball, *B*, is in the slanting direction, *BP*, we may think of this pull as divided into two parts, an upward pull (in the direction *BL*, Figure 21) and a centripetal pull (in the direction *BI*). The upward pull supports the weight of the ball, and the centripetal pull forces it to curve its path continually toward the pole, thus moving in a circle.

Centripetal force on an airplane

In the case of an airplane, as in the case of a ball, in order that the plane will move in a circle it must have a force acting on it continuously in the direction of the center of the circle. In other words, it must have some force acting at right angles to the path of the plane.

Now when a plane is banked, the force of the air on the wings (which is always perpendicular to the lateral axis) is in a slanting direction, as shown by the direction of *OW* in Figure 22. This slanting force, *OW*, on the plane has the

FIG. 22. The force of lift on an airplane, divided into a sustaining force and a centripetal force.

effect of being partly a sustaining force, *OS*, opposite to gravity and partly a sideward-pulling force, *OC*. The sustaining part of the force supports the weight of the plane; and the sideward-pulling part of the force, when kept directed toward a point (the center of a circle) by yawing and pitching (as later explained), becomes a centripetal force causing the plane to move in a circle, as shown in Figure 23.

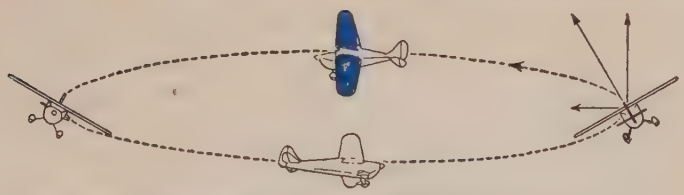


FIG. 23. Sustaining force and centripetal force acting on a plane flying in a circle.

Why, then, is a plane banked in order to make a turn? This is the scientific answer to the question. It is banked so that part of the effect of the pressure of air under the wings will act as a sideward force on the plane; and when this sideward force is kept directed to a point by yawing and pitching, it becomes a centripetal force — the kind of force necessary to make the plane move in a circle.

More power needed for a turn

Obviously just as much sustaining force (opposite to gravity) is needed during a turn as in straight flight. (The sustaining force always equals the weight of the plane in uniform flight.) But since a turn requires that the wings contribute the centripetal force also, the total lifting force of the wings must be greater than the sustaining force only. And it takes more power to give the wings more lifting force (at the same speed); hence it takes more power to make a turn than to fly straight at the same speed.

The greater the speed the greater the bank

When flying a circle of a given radius, the faster the flight the more banking is required. It is for a similar reason that race tracks for automobiles are banked steeply on turns which could be made at moderate speeds with little or no banking. A racing plane in making a sharp curve is so steeply banked that it looks almost vertical.

Questions

1. Why is an automobile race track banked at sharp turns?
2. What happens when a plane is yawed without being banked?
3. How does a plane skid?
4. Show that a force operating toward the center is needed to make a body move in a circle.
5. What is meant by a centripetal force?
6. What is meant by a centrifugal force?
7. How can the pilot tell when a plane is properly banked?
8. What is meant by a plane slipping?
9. Which requires more banking, a sharp turn or a gradual one?
10. How may a pilot judge the proper angle of bank by the feel?
11. Why does the horizon sometimes appear tipped, and not the plane?
12. How many control motions are required in a normal turn?
13. What is the pivotal altitude?
14. Is centripetal force acting on the end of a whip that is cracked?
15. Is centripetal force acting on a bowling ball as it rolls?
16. Mention several situations in which centripetal force is acting.
17. When making a turn of given radius, which takes more banking, greater speed or lesser speed?

Air Associates, Inc.

Fig. 24. A tachometer.

4

BASIC INSTRUMENTS USED IN FLYING

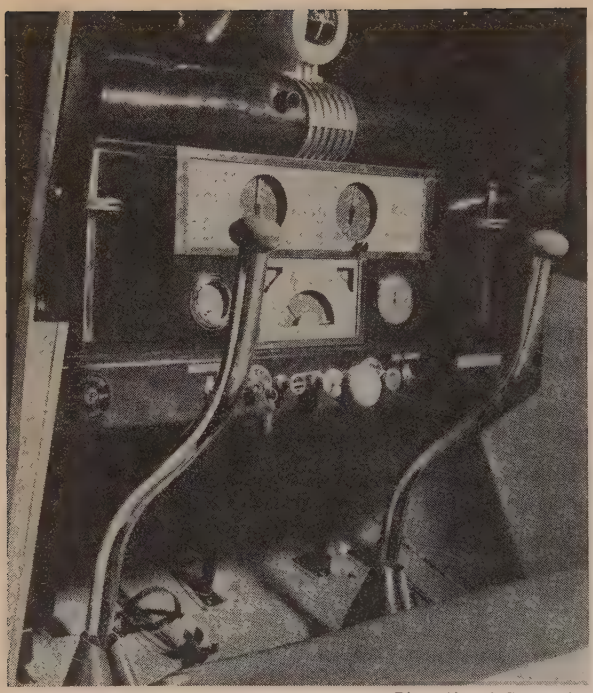
THE four most important instruments used in an airplane are the tachometer (tăchŏ′meter), air-speed indicator, altimeter (ăl′tĭme′ter), and compass. The tachometer measures the speed of the engine; the air-speed indicator measures the speed of the plane through the air; the altimeter measures the altitude of the plane; and the compass indicates the direction of the plane.

The tachometer

The tachometer, as shown in Figure 24, is an instrument to show the number of revolutions per minute that the engine is making. (In light planes the propeller is usually fastened directly to the engine crankshaft and revolves just as fast as the crankshaft.) If the dial hand points to the number 21, it means that the propeller is revolving at the rate of 2100 revolutions a minute (RPM).

An engine may be capable of turning 2300 revolutions a minute; but 2100 may be the proper cruising speed, because it is not good for an engine to force it to revolve at full speed for continuous flying. Full power is used ordinarily only at the take-off.

The pilot looks at the tachometer occasionally while flying, to see whether or not he is racing his engine unnecessarily or whether the engine is slowing. If the tachometer shows a loss of "revs" while flying, this may be a sign of danger because of loss of power and should be investigated. The cause may be icing in the carburetor or an unintentional climb or some other condition.



Piper Aircraft Corporation

FIG. 25. The instruments in place in a light plane, which is not equipped for "instrument flying." At the top is the compass. In the next row are the airspeed indicator (left) and altimeter (right). The semicircular dial in the center of the picture is the tachometer. The triangular dials near the tachometer are the fuel-temperature and fuel-pressure dials. In the same row are a clock and a battery dial. The knob below the tachometer is the throttle. The curved rod on each side is a "stick."

Principle of the tachometer

The principle on which a common form of tachometer works is somewhat similar to that of the governor on a steam engine. The instrument responds to centrifugal force.

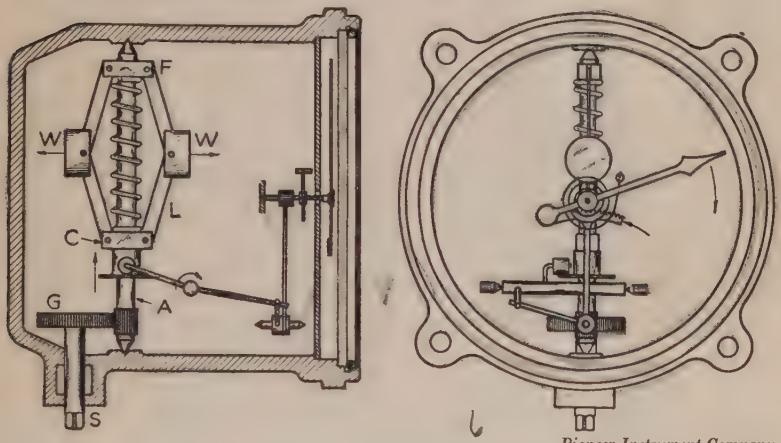
The rotation of the engine is carried to the gear G (Fig. 26) by means of a flexible shaft. Gear G turns axle A at a higher rate. Flyweights W are mounted on the ends of links L, which are also connected to the two collars F and C. The collar F is fastened to axle A at the top. Collar C slides up and down on the axle.

The coiled spring around the axle tends to hold collar C down; but as the axle rotates, the weights tend to fly apart and lift collar C against the spring. The greater the speed of the engine and of the axle, the more collar C is lifted.

The motion of collar C up and down is carried to the dial hand by means of levers as shown, thus indicating the number of revolutions per minute. The hairspring attached to the

dial hand prevents fluctuation of the pointer and brings it back to zero when collar *C* falls.

Other types of tachometer are electrically operated.



Pioneer Instrument Company

FIG. 26. A diagrammatic representation of the mechanism of a tachometer.

Stalling speed

As you will understand more fully later, a plane will stall if it loses flying speed. A plane may lose flying speed either because the pilot tried to climb too steeply for the power of the engine, or because he tried to fly level too long without power, or because he tried to turn too sharply, or for some similar reason. The speed at which a plane will stall is called the *stalling speed.* We may think of the stalling speed of a plane as being slightly less than the minimum flying speed.

Air speed

The flying speed or stalling speed of a plane is wholly a matter of its speed *with reference to the air.* The speed of a plane with reference to the air is called the *air speed* of the plane. The air speed of a plane is not necessarily the same as its speed over the ground because there is often *wind drift.*

Wind drift

When a plane is flying through the air, the air itself is usually moving and therefore helping the plane or hindering it. If you were walking at the rate of 4 miles an hour on the top of a freight car that was moving in the opposite direction at the rate of 1 mile an hour, you would be moving forward at the rate of only 3 miles an hour with reference to the ground. The freight car would be carrying you back 1 foot for each 4 feet that you walked forward.

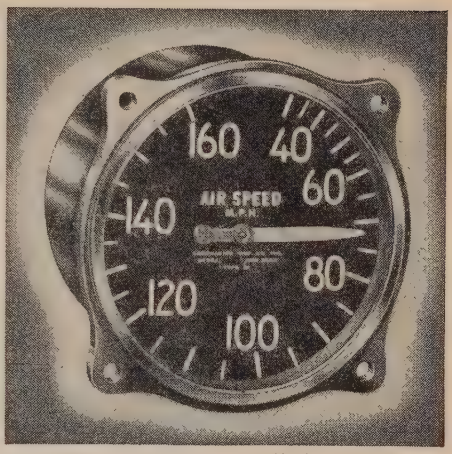
If the freight car were moving at the rate of 1 mile an hour in the same direction with you, you would be going 5 miles an hour with reference to the ground. The car would be carrying you forward 1 additional foot while you walked forward 4 feet.

So, if the wind is blowing at the rate of 10 miles an hour northward, a plane flying southward at 60 miles an hour is moving over the ground at only 50 miles an hour. We say it has a *head wind.* If the plane flies northward at 60 miles an hour in the same wind, it can go 70 miles an hour over the ground. We say it has a *tail wind.* The additional movement that the wind gives to a plane is called *wind drift.* You will learn more about wind drift in Chapter 23.

The air-speed indicator

It is not easy under all circumstances to tell soon enough when a plane is getting ready to stall. The principal reason is that since we cannot see the motion of the air, it is difficult to judge how fast the plane is moving through the air. Therefore it is a good idea to have an instrument with a dial to indicate the speed of the plane through the air. Such an instrument is called an *air-speed indicator.* Figure 27 shows the dial of an air-speed indicator. If the dial hand points to 60, it shows that the air speed of the plane is 60 miles an hour.

You should know the stalling speed of a plane before flying it. If the stalling speed of a plane is 40 miles an hour, you should take a look at the air-speed indicator whenever you are in doubt, to make sure that your air speed is well over 40 miles an hour.



Air Associates, Inc.

FIG. 27. An air-speed indicator.

Eventually a pilot learns to judge his air speed by the feel of the controls (ailerons, rudder, etc.) and by the sound of the air rushing past the cockpit and the struts. If the motion of the rudder does not produce the usual amount of turning, or if the sound of air whistling past the struts dies down a little, it means you are losing air speed and are in danger of stalling.

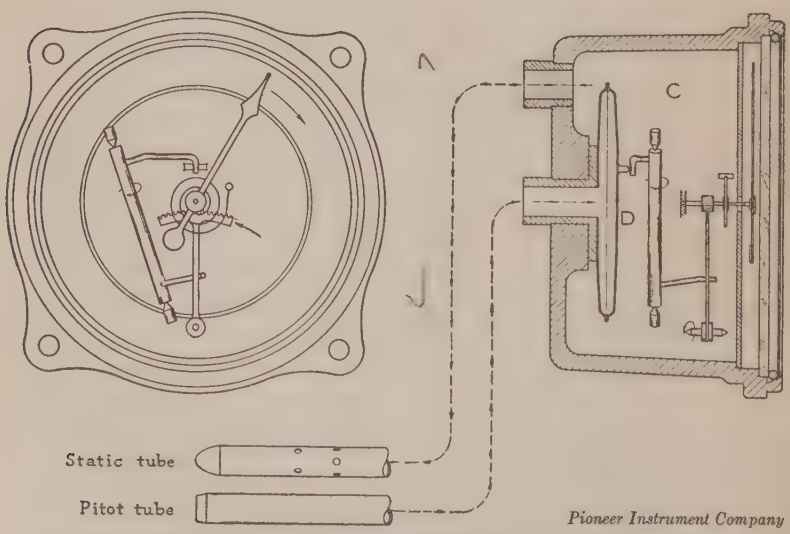
The air-speed indicator cannot tell your speed of flying over the ground; it can only tell your speed through the air. The air-speed indicator may show that you are flying at 60 miles an hour (north, let us say); but if the wind is blowing south at 60 miles an hour, the plane will be standing still over the ground. If in such a case the wind is blowing 70 miles an hour, instead of 60, the airplane headed north will actually be moving backward (south) at 10 miles an hour. Pilots have flown backward in this manner.

Always remember that whether or not a plane stalls does not depend in the least upon speed over the ground; it depends entirely upon air speed. If you are traveling through the air at 60 miles an hour, you are probably in no danger of stalling, even though you are barely moving forward over the ground, as is the case when you have a very strong head wind.

On the other hand, you might be going 80 miles an hour with reference to the ground and still stall. Thus, if you were flying north in a wind blowing northward at 50 miles an hour and your air speed was reduced to 30 miles an hour, you would undoubtedly stall even though your speed over the ground was 30 + 50 or 80 miles an hour.

Principle of the air-speed indicator

The action of the common air-speed indicator is based on the difference between the pressure of still air and the increased air pressure produced by the forward motion of the plane. At the height at which the plane is flying, the pressure of still air is called the *static* pressure; and the increased pressure, produced by the onrush of air on the front of the plane, is called the *dynamic* pressure. The difference between these two pressures is measured by the air-speed indicator.



Pioneer Instrument Company

FIG. 28. A diagrammatic representation of the mechanism of an air-speed indicator.

The air-speed indicator consists essentially of an airtight chamber (chamber *C* in Figure 28) containing a smaller airtight chamber *D* called a *capsule* or diaphragm. A tube called the *static* tube is connected with chamber *C* and another tube called the *pitot* tube (pronounced pē-tō′) is connected with the capsule. As shown in Figure 28, the two tubes project forward, usually from a wing strut, in advance of the leading edge of the wing and away from the slip stream of the propeller.

The *static* tube is closed at the end but has holes at the sides. Air does not tend to flow either in or out of these holes, and the pressure of air throughout the tube is the same as that of the air through which the plane is flying. This pressure is the static pressure of the air.

The *pitot* tube is open at the end. The onrush of air toward the plane [1] tends to crowd into the tube and thereby creates a greater-than-static pressure. This is the dynamic pressure. Obviously at a given altitude, the greater the speed the greater the dynamic pressure.

The dynamic pressure exceeds the static pressure as the plane moves forward, and the capsule necessarily expands. The greater the speed, the greater the expansion of the capsule. The motion of the movable side of the capsule is transmitted to the dial hand of the instrument, indicating the changes in dynamic pressure which occur with changes of air speed.

Correction for altitude

Air-speed indicators are graduated (scaled) to indicate the speed of the airplane at sea level at normal temperature (16° C.). But at higher altitudes, where the air is less dense, the difference in pressure between the two tubes is less for a given air speed than it is at sea level. Hence the air speed indicated at altitudes above sea level is less than the true air

[1] Thinking of the plane as if it were stationary and the air were moving toward it.

speed. (A means of determining altitude is described below.)

The reduction in indicated air speed is about 1.5 per cent for each 1000 feet. Hence to find the true air speed an approximate correction can be made to the indicated air speed by adding 1.5 per cent to the indicated air speed for each 1000 feet of altitude. Thus, if at 6000 feet the air speed indicated is 100 miles an hour, the correction is 6 × 1.5 per cent, or 9 per cent. Nine per cent of 100 miles is 9 miles. Hence the true air speed is about 109 miles an hour.

Roughly, the rule works the other way also. That is, if the true air speed at 6000 feet is 100 miles an hour, the indicated air speed is about 9 per cent less, or about 91 miles an hour.

Figure 29 provides a more accurate means for finding the true air speed that corresponds to a given air speed reading obtained at a given altitude. For example, let us say we are flying at 10,000 feet and the indicated air speed is 86 miles an hour. To find the true air speed, proceed as follows:

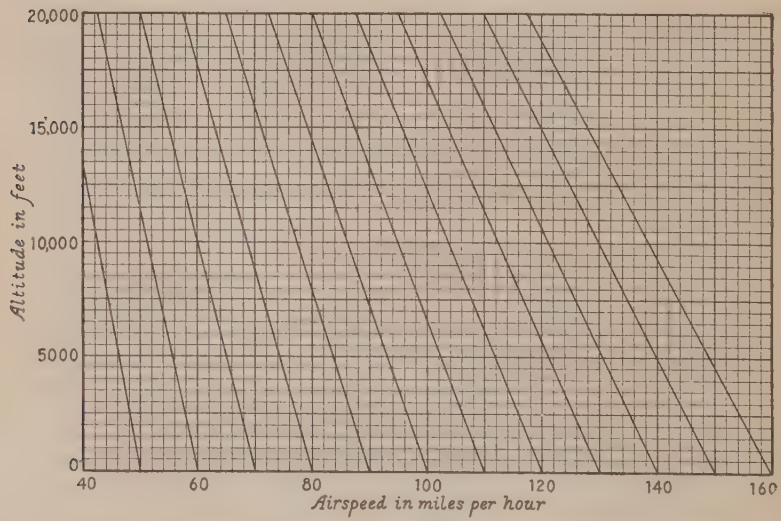


FIG. 29. A chart for use in correcting the air speed for altitude.

1. Find the vertical line representing an air speed of 86 miles an hour according to the scale at the foot.
2. Follow this vertical line upward until you come to the horizontal line representing 10,000 feet, according to the scale at the left.
3. Find the slanting line which passes through the intersection of these horizontal and vertical lines, and follow this down to the foot of the graph.
4. Read the air speed at this point. It is the true air speed. In this case it is 100 miles an hour.

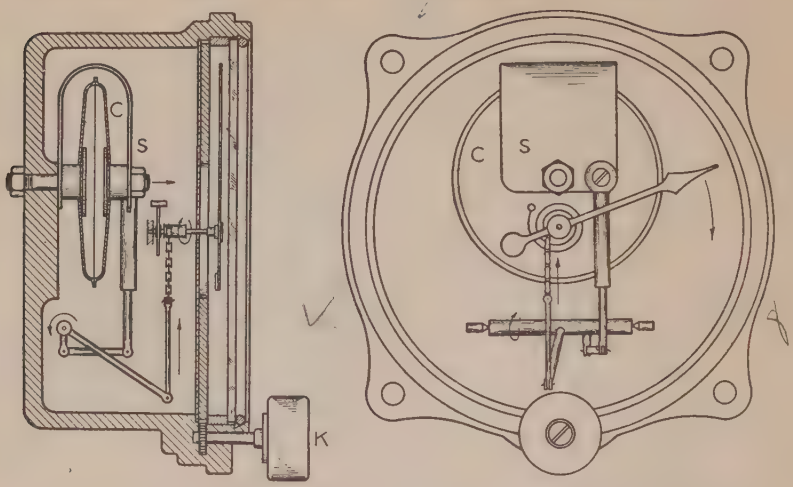
Air Associates, Inc.

FIG. 30. The altimeter.

The altimeter

There are times when a pilot must know how high he is above the ground. For example, the Department of Commerce rules require that a pilot fly not less than 1000 feet above congested areas of cities and not less than 3000 feet above an airport when flying directly over it. The altimeter, shown in Figure 30, enables the pilot to know how far the plane is above the ground. If the dial hand points to 2, it means that the plane is at an altitude of 2000 feet.

The position of the dial hand of the more common type of light-plane altimeter is determined by the air pressure and cannot be manipulated. But the scale to which the hand points can be revolved by a thumbscrew and set so that the hand points to zero when the plane is on the ground. The altimeter then shows in flight the altitude of the plane above the home airport. Or the scale can be set so that



Pioneer Instrument Company

FIG. 31. A diagrammatic representation of the mechanism of an altimeter.

with the plane on the ground the hand points to the altitude of the airport. The altimeter then shows the altitude of the plane above sea level.

Principle of the altimeter

The altimeter depends for its operation on the fact that the pressure of the air decreases as altitude increases. An altimeter is merely a form of aneroid barometer graduated to show not inches of mercury but feet of altitude.

As a result of many observations the average relation between altitude and barometric pressure has been determined, and the figures have been published by the Bureau of Standards. These figures are used for calibrating all altimeters; that is, the altitude indicated by the altimeter is the most probable altitude corresponding to the air pressure which is being exerted upon the altimeter. Since the air pressure changes from day to day, some altimeters are made so that they can be adjusted according to sea-level

air pressure. Those not so adjustable give only approximate indications of altitude.

The essential features of an altimeter are shown in Figure 31. Fastened to the wall of chamber *C* of the instrument there is an airtight capsule, *C*. The capsule is exhausted of air (contains only a vacuum) and is held from collapsing from pressure outside it by a spring *S*. The air in the chamber outside the capsule is at static pressure for the given altitude, the chamber being in most cases connected to a static tube, which may be the same static tube that goes to the air-speed indicator.

As the plane gains altitude, the air in the chamber exerts less and less pressure and hence tends less to collapse the capsule. This allows the spring to expand the capsule. The motion of the capsule and spring is carried by levers and a small chain to the dial hand, as shown in the figure. The greater the altitude, the less the pressure of air upon capsule *C* and the farther the dial hand moves.

The compass

It is ill advised to attempt any extended flight over unfamiliar territory without a compass, especially in cloudy weather when the sun does not serve to keep you oriented (to keep your directions straight). This is because it is very easy to become disoriented (turned around)—thinking that north is east, for example. If you go in the wrong direction and get lost, there is no one to ask which way is north! Figure 32 shows a compass of the kind commonly used in planes.

In this compass a vertical line called the *lubber line* in the middle of the compass face is

Air Associates, Inc.

FIG. 32. The compass.

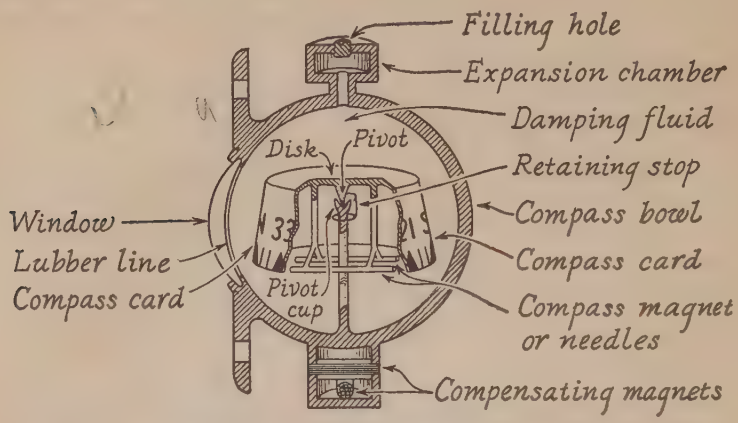


FIG. 33. A diagrammatic representation of the mechanism of an airplane compass.

stationary and the scale moves. The scale is graduated from 0° to 360°, 0° being north.

The scale marks of the compass shown in Figure 32 with their meanings are as follows:

SCALE MARKS:	N	33	30	W	24	21	S	15	12	E	6	3	N
MEANING:	360°	330°	300°	270°	240°	210°	180°	150°	120°	90°	60°	30°	0°

If the number 3 on the scale is under the lubber line, it shows that you are headed in a direction 30° clockwise from north. In this discussion we assume that the compass is correct and that magnetic north is true north. Corrections to be applied when the magnetic north is not the true north are discussed in Chapter 17.

If a line drawn on your map from where you are to where you want to go points 60° from north, you turn the plane till the compass reads 6 (60°). That is the direction in which you should fly.

Principle of the compass

The common airplane compass operates on the same principle as the ordinary compass which consists of a magnetized

needle balanced and free to point toward magnetic north. In the airplane compass the scale is on a cylindrical card which is mounted upon the needle and turns with it.

The important elements of the airplane compass are shown in Figure 33. A bowl has at its center a pivot cup in which a pivot rests. The pivot supports a disk. On the outer edge of the disk the cylindrical or cone-shaped compass card is attached. Suspended from the disk are two magnetic needles, one on each side of the pivot-cup support. A damping fluid fills the bowl and retards, or damps, any oscillations of the compass. The compass card is seen through a window in the front of the compass; a vertical white line, the lubber line, which may be painted on the inside of the window, serves as a pointer for the scale. The needles, disk, and scale are free to rotate so that the needles may always point to magnetic north. When the plane turns, only the bowl of the compass turns with it, and not the needles or the scale.

Compensating magnets

The compass needle is affected not only by the earth's magnetism but also by any iron or steel that may be near,

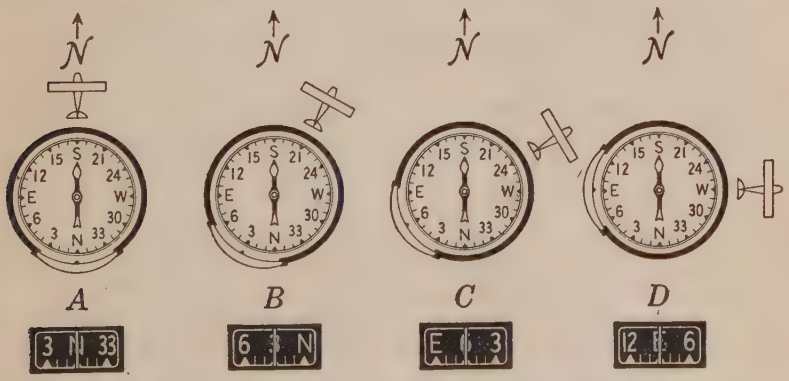


FIG. 34. A diagrammatic top view of an airplane compass, in four positions, showing how the window appears in each position.

such as the engine. To counteract this effect, additional magnets are placed in a compartment below the bowl. These *compensating magnets* partially overcome deviations of the compass needles caused by the nearness of iron or steel.

An expansion chamber at the top of the compass provides space for the expansion of the damping liquid which may be caused by changes in temperature.

Figure 34 represents diagrammatically a compass with the plane headed north at *A*, 30° east of north at *B*, 60° east of north at *C*, and due east at *D*. At *A* the lubber line in the middle of the window, represented by a dot, is opposite the N, indicating that the plane is headed north. At *B*, with the plane headed 30° east of north, the compass still points north, but the window is moved around so that the lubber line (dot) is opposite 3, indicating a heading of 30°. The window then appears as shown below *B*. And so on.

This means that as a gradual turn [1] is made from north to east the compass card is moving to the *right* in the window.

The bank indicator

The method of banking by means of the sensation of how one is sitting in the plane, as explained in Chapter 2, is not very exact; and some persons are not good at judging whether or not they are sitting perpendicular to the seat, especially when the horizon appears tilted with reference to the plane. Hence some planes are equipped with a bank indicator, as shown in Figure 35. It consists of a curved glass tube containing a metal ball in a damping fluid. If the plane is banked properly, the ball will stay in the mid-

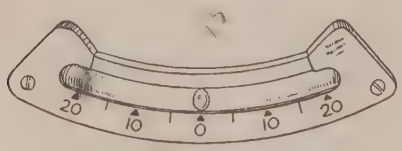


Fig. 35. The bank indicator.

[1] See Chapter 39 regarding the northerly turning error, a compass error occurring with a banked turn.

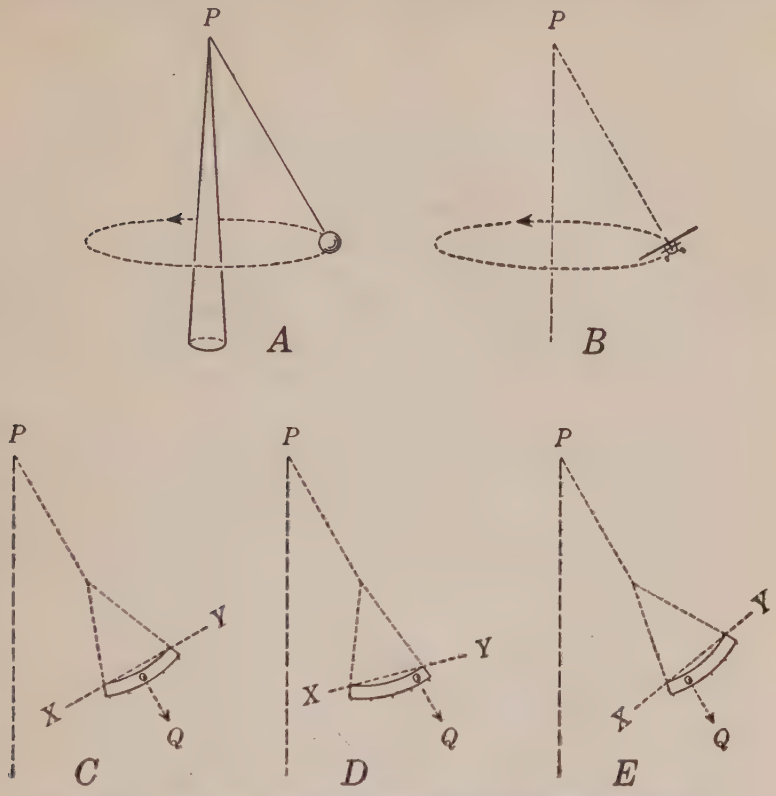


FIG. 36. The principle upon which the bank indicator works.

dle of the tube at the arrow. If in a right turn the plane is not banked enough, the ball will move to the left; if banked too much, the ball will move to the right.

The indicator does not tell the pilot how much the plane is banked or even whether it is banked or not. It tells only whether the plane is banked correctly for the airspeed and radius of turn.

Many light planes are without a bank indicator, and ordinarily one can judge approximately the proper amount of bank by the feel.

Principle of the bank indicator

A plane is properly banked for a given air speed and radius of turn if it is banked so that its normal axis is parallel to a wire that is holding a ball turning in a circle at the same speed and radius of turn as the airplane, as shown at *A* and *B* in Figure 36 on the preceding page.

If the plane is making a turn, as shown at *B* in Figure 36, any weight in the plane such as the steel ball in the bank indicator will tend to be pulled in the direction of the wire (direction of arrow *PQ* at *C* in Figure 36). The force doing this pulling is a combination of gravity and the centrifugal force.

The bank indicator is set parallel to the lateral axis of the plane, and if the plane is properly banked so that its lateral axis (*XY* in Figure 36) is perpendicular to *PQ*, the steel ball will take a position in the middle of the glass tube, as shown at *C*; otherwise it will be off center, as shown at *D* and *E*.

Oil-temperature gauges and oil-pressure gauges

The instrument panel of a plane contains also gauges indicating the oil temperature and oil pressure. Before flying a plane, it is necessary for safety to have the engine thoroughly warmed up by running the engine. In the case of light planes, an oil temperature of 100° Fahrenheit is usually considered sufficient. The oil-temperature gauge tells when the desired temperature has been reached in the warm-up.

The oil-pressure gauge enables the pilot to note whether the engine is being properly lubricated.

Thermometer

Many pilots like to have an ordinary air-temperature thermometer installed outside the cockpit (as on the wing strut), so that they may note the temperature of the air. It

is important to know when the temperature of the air is near the freezing point — when icing on the wings may occur.

Fuel gauge

It is important that the pilot be able to determine at any time the amount of gasoline available. A fuel gauge is therefore needed. The simplest type consists merely of a cork or airtight metal chamber floating on the gasoline, with a wire stem projecting through the tank cap. As the gasoline is used up, the wire stem sinks. Or the vertical motion of the float may be transmitted to a dial or other indicator in the cockpit to show the amount of fuel available.

QUESTIONS

1. What does a tachometer measure?
2. On what principle does it work?
3. What speed of revolution does 21 on the dial mean?
4. Would a plane be likely to cruise at 190 or 1900 or 19,000 revolutions a minute?
5. What might cause a loss of revs?
6. What instrument measures the speed through the air?
7. What is the principle on which the air-speed indicator works?
8. What does 60 mean on the air-speed indicator?
9. Would a head wind decrease or increase the air speed of a plane?
10. Would a head wind decrease or increase the speed of the plane over the ground?
11. Could a pilot under any circumstances fly a plane without moving forward over the ground?
12. Could a plane stall while flying at a speed of 100 miles an hour over the ground?
13. What is a static tube?
14. What is a pitot tube?
15. What is a capsule?
16. At 5000 feet does the air-speed indicator indicate greater or less speed than at 2000 feet if the true air speed is the same in both cases?

17. If a plane is cruising with a true air speed of 100 miles an hour, about what air speed will the indicator show at 8000 feet?
18. What instrument measures altitude?
19. What altitude does the number 4 on the altimeter indicate?
20. What is the principle on which the altimeter works?
21. Does an altimeter ever show different altitudes at different times at the same airport? Why?
22. What does the compass indicate?
23. What is the lubber line?
24. What does 30 on the compass scale indicate?
25. What is it that turns relative to the ground when the plane changes direction, the compass bowl or the compass card?
26. What is a damping fluid? Why is it used?
27. What does a bank indicator show?
28. If a pilot is turning to the right and the ball is at the left in the indicator, is the plane skidding or slipping?
29. If a plane were properly banked, would a plumb bob in the cockpit point vertically toward the ground?
30. Why might a pilot need to know the temperature of the air through which he was flying?
31. If a pilot is flying north with an air speed of 100 miles an hour and the wind is blowing south at 20 miles an hour, what is his ground speed?

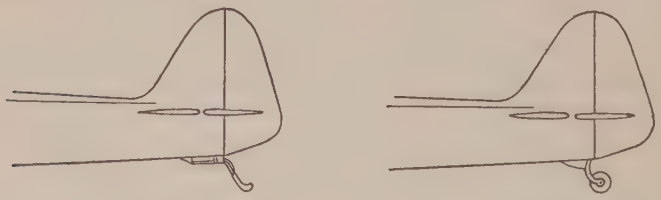


FIG. 37.

5

STARTING — TAXIING — TAKE-OFFS

A CERTAIN amount of maneuvering of a plane on the ground is necessary, of course. A plane can propel itself on the ground by the force of the propeller alone. Moving a plane on the ground by means of the propeller is called *taxiing*.

Landing gear

The conventional plane has two wheels near the front, which are like the two front wheels of an automobile except that they do not turn from side to side but always point straight ahead.

These two wheels together with their supports and the springs between the wheels and the fuselage (body) of the plane are called the *landing gear*.

In many planes there are brakes on these front wheels, one brake on each wheel. Each brake is operated by a foot pedal. To stop the right wheel, you push the right brake pedal. To stop the left wheel, you push the left brake pedal. Pushing both pedals stops both wheels, of course.

Tail support

At the tail of the plane there is a small third wheel or else a *skid*, to hold up the tail.

The skid is just a springy piece of metal that drags along the ground. (See Fig. 37 on the preceding page.)

Tail wheels are of two varieties, swivel and steerable. A swivel tail wheel works just like the caster on a bed. It

turns in any direction that it is pushed. A steerable tail wheel moves with the rudder and is always parallel with it.

The throttle

The speed of the engine is regulated by a throttle. The handle of the throttle is sometimes a knob on a stem sticking out of the instrument board, as shown in Figure 38; or it may be a knob on a lever at the side of the cockpit. The handle itself is often spoken of as the throttle.

When the throttle (knob) is pulled out, it is said to be closed; that is, it allows only a small amount of gasoline to go into the engine and the engine can only idle. When the throttle is pushed in, it is said to be open. The thing that is open is really a valve that regulates the amount of gasoline that goes into the cylinders. The farther in you push the throttle, the more gasoline is fed to the engine and the faster the engine and propeller turn. In speaking of gasoline we mean the mixture of gasoline vapor and air.

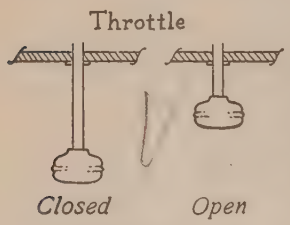


FIG. 38.

Starting the engine

When you intend to start the engine, look at the gasoline gauge to make sure that you have plenty of gasoline; see that the gasoline switch is on, so that gasoline can flow from the tank to the carburetor; see that the throttle is closed, or nearly so, so that the engine will not race when it is started. It is usually necessary to turn the engine a few times by hand to prime it. Before this is done see that the ignition switch is off, so that no spark will be generated as the engine is turned over. Blocks called "chocks" (see Fig. 39) must be in place in front of the wheels to prevent the plane from rolling forward before you are ready. Or the parking brake,

if any, must be on; or you must have your feet on the brake pedals. If the plane has no self-starter, an attendant is needed to start the engine by spinning the propeller.

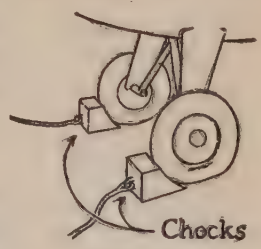


Fig. 39.

When you are ready, you say to the attendant, "Gas on, switch off." The attendant then steps to the front of the plane, turns the propeller a few times, and calls, "Contact!" This is a signal for you to turn on the ignition switch, causing the spark to occur in the spark plugs. You turn the switch, place your hand on the throttle in order to be ready to readjust it quickly if necessary, and answer, "Contact!" The attendant then spins the propeller and the engine starts.

That is, it is supposed to start! If it doesn't, additional priming is necessary. The cause of the engine's failure to start may be lack of enough fuel in the cylinders or too much fuel in the cylinders.

Usually the attendant assumes first that there is not enough fuel in the cylinders, and he turns the propeller forward a few times more with the switch off, then again tries to start the propeller with the switch on.

If this fails, the attendant will assume that the engine is flooded and will say, "Off and open," meaning that you are to turn the switch off and open the throttle. He will then turn the propeller a few times with the throttle open to draw out the excess fuel vapor.

"Gas on; switch off"

It is very important to form the habit of saying, "Gas on, switch off." Pilots have made the mistake of thinking only of the ignition switch, forgetting to turn on the gas lever and having the engine suddenly stop as soon as the gasoline in the carburetor was used up. Or they have turned on the

gas-supply lever and forgotten to note the position of the ignition switch. It is very dangerous for the ignition switch to be on when the attendant is merely priming the engine and assumes the switch to be off. The propeller may strike his arm and break it before he is aware of what is wrong.

The habit of placing your hand on the throttle is a precaution against saying "Contact" with the throttle open. It is dangerous for the attendant to start the engine with the throttle open. The plane may move forward suddenly before the attendant can get out of the way.

Warming the engine

It is of vital importance that the engine be thoroughly warmed up before taking off. A cold engine is much more likely to stop than a warm engine. It is well to do this warming up before taxiing to the end of the runway. If the plane has not been flown recently, you may need to let the engine run for as long as ten minutes to warm it thoroughly. The oil-temperature gauge on the instrument board enables you to know when the engine is warm enough to fly safely. An oil temperature of 100° F. is usually sufficient in the case of a light plane.

When the engine is warm enough, you are ready to taxi to the runway.

Taxiing

The flying student is usually much surprised to find what a hard time he has to taxi a plane at first. One reason for this is that although a plane is steered in the same manner on the ground as in the air — press right pedal for right turn, and press left pedal for left turn — you will discover that it takes much more foot pushing to steer the plane when taxiing than when flying.

When there is a strong rush of air past the rudder, as in flying, the plane turns quickly on a slight push of the rudder

to one side. But when taxiing there is no such strong rush of air past the rudder. If the plane has a steerable tail wheel, this helps steer the plane; otherwise there is only the breeze created by the propeller to turn the plane. Consequently you have to do much more footwork to keep the plane straight. More footwork is necessary for taxiing than for flying even when you have a steerable tail wheel.

Another difficulty in your first taxiing arises from the fact that it takes less turning of the rudder to turn the plane after it has once started to turn than when it is just beginning to move. So if you are not careful, you will turn the plane too far.

A third difficulty is that in taxiing a plane, especially one with a swivel tail wheel, the plane has a tendency to keep on turning after you have straightened the rudder. The tendency exists to a degree in flying, but it is more noticeable in taxiing. When you straighten the wheels of an automobile, it stops turning, but, as we have said, when you straighten the rudder of a plane, the plane will turn a little farther before going straight. The explanation consists in the fact that the sideward movement of the tail which turns the plane is not entirely stopped by merely straightening the rudder. The momentum of the plane makes it continue to turn after the rudder is straightened and air resistance is slow in acting to stop the turning.

If you are taxiing west in a plane and wish to go north, you turn the plane by pushing on the right foot pedal and giving the rudder a blast of air from the propeller; but when you have the plane only *part* way turned to the north, you must straighten the rudder by ceasing to push on the pedal, so that the plane can get over its tendency to turn by the time it points north. You may even have to push on the left pedal and give the left side of the rudder a little blast of air from the propeller to keep the plane from turning past north. It takes quite a little practice taxiing in order to learn just

how far the plane will continue to turn after you have straightened the rudder, so that you can make the plane turn the amount you wish it to turn but not too much.

Side wind when taxiing

If the wind is blowing against the right side of the plane, it has a tendency to swing the tail of the plane to the left, causing the plane to turn to the right. This adds to the difficulty of taxiing straight ahead.

When taxiing against the wind, you will find that the ailerons will help keep the plane straight. If, then, you wish to turn the plane slightly to the right, you will find that by pulling down the right aileron (by pushing the stick to the left) the aileron will act as a brake. The greater air pressure on the turned-down aileron retards the right wing and helps turn the plane to the right. This movement of the ailerons is just the opposite of the movement made in banking for a right turn. (To bank for a left turn, move the stick to the left; but to taxi to the left against the wind, move the stick to the right.)

If the plane has only a swivel tail wheel — not a steerable one — it is necessary sometimes in a stiff breeze to turn the plane in the opposite direction from that in which you wish to go. Thus, suppose the plane is facing west and the pilot wishes to taxi north. Suppose a strong south wind is blowing (pushing the tail to the right). The pilot may not be able to turn the plane to the right. He will therefore make a quick turn to the left (having the wind to help him) and will turn the plane to the south, then to the east, then to the north. The momentum of the tail obtained in the first part of the swing helps to carry the plane around.

If there is not room to make a turn in this way, the pilot may require an assistant to hold the tip of the right wing while he turns the plane to the right.

Since every flight requires taxiing, both to the point of

starting and back from the point of stopping, the student gets plenty of practice in taxiing along with flying practice.

Taking off into the wind

In taking off (leaving the ground), you always face into the wind. That is, you point the plane in the direction *from which* the wind is blowing. The reason for this is that you can get up flying speed with less ground speed.

For example, suppose flying speed for your plane is 60 miles an hour. That means you must be going 60 miles an hour (air speed) in order to take off.

Now if the wind is blowing at the rate of 15 miles an hour toward the west and you try to take off toward the west, when you get up a speed of 60 miles an hour with reference to the ground you are moving at the rate of only 45 miles an hour with reference to the air — not enough air speed to lift the plane. (We have already explained how an air speed of 45 miles an hour plus 15 miles an hour gives a ground speed of 45 + 15 or 60 miles an hour.) You would have to get up a ground speed of 75 miles an hour for a speed through the air of 60 miles an hour. This would require a much longer runway than ordinary and is not as safe.

On the other hand, if you take off toward the east, the direction *from* which the wind is blowing, then when you are going only 45 miles an hour with reference to the ground, the wind is blowing past the wings at 45 + 15 or 60 miles an hour. That is enough to lift the plane.

If the wind is blowing westward at 20 miles an hour, an eastward ground speed of only 40 miles an hour will give 60 miles an hour air speed — enough to lift the plane. The faster the wind is blowing the less ground speed is needed to get into the air when taking off upwind (against the wind). In fact, if the wind were blowing westward at 60 miles an hour and you had a plane with a flying speed of 60 miles an hour roped to the ground and facing east, theoretically all

you would need do to take off would be to start the engine, cut the ropes, and fly straight up.

The reason, then, that we take off *upwind* is that it takes less ground speed and is therefore safer. Downwind take-offs are made only under special conditions, as when the wind is light and there are fewer obstructions at the downwind end of the runway or field.

As for taking off crosswind, as northward when the wind is westward, that adds a complication because the plane is blown sidewise. A skillful pilot can overcome this tendency to be blown sidewise by a judicious use of the ailerons, but only in a moderate crosswind. This is explained in Chapter 10 on crosswind take-offs and landings.

Noting the wind direction

The direction of the wind at an airport is usually shown by a *wind sock*, a canvas tube flying in the wind from a pole on top of the hangar or elsewhere near the airport (Fig. 40). Before taking off, therefore, you always look at the wind sock to see which way the wind is blowing. Then you take off into the wind, or upwind.

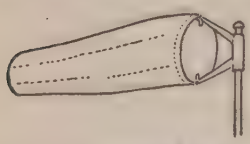


FIG. 40. A wind sock.

It is easy for a beginner to become confused about the direction in which to take off. He says to himself, rightly enough, "The wind is blowing toward the east," and then he proceeds, wrongly, to take off toward the east. It is quite worth while to learn a simple way to determine the direction of take-off without thinking about wind direction. Just look at the wind sock and think, "I must take off into the loose end." (See Fig. 41.)

Runways in different directions

A good airport usually has at least four runways, one north and south, one east and west, and two diagonal, as shown

in Figure 42. This enables the pilot to choose a runway that points reasonably close to the direction that happens to be

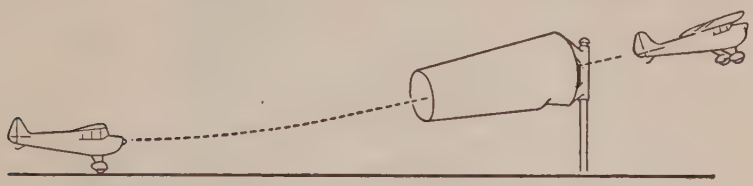


FIG. 41. A help in thinking which way to take off.

into the wind. A little variation from directly into the wind is not serious, especially if the wind is not strong.

To take off, select the runway that comes nearest to pointing into the wind and taxi to the downwind end of the runway. (Students have selected the right runway but gone to the wrong end to take off!)

Taking off

Briefly stated, the steps in taking off are as follows: First you get up speed with all three wheels (or the two wheels and the skid) on the ground. Next you "lift the tail" of the plane to bring it to a level flying position (it was pointing considerably nose-up when on three wheels), and you let the plane run along on two wheels until it gets up flying speed. Then you gently raise the plane off the ground, as we say. You let it fly level a moment to get up still more speed, then begin a gradual climb. When high enough, level off. These steps are explained more fully below.

When you have selected the proper runway and reached the end for the take-off, have a good look around before turning into the wind, to make sure that no plane is about to land. Planes land up wind also and therefore use the same runway in the same direction as you will take off. Then, if no plane is approaching to land, turn the plane until it is pointing directly down the runway. Push the throttle gradually all the way in with one hand, while you steer the

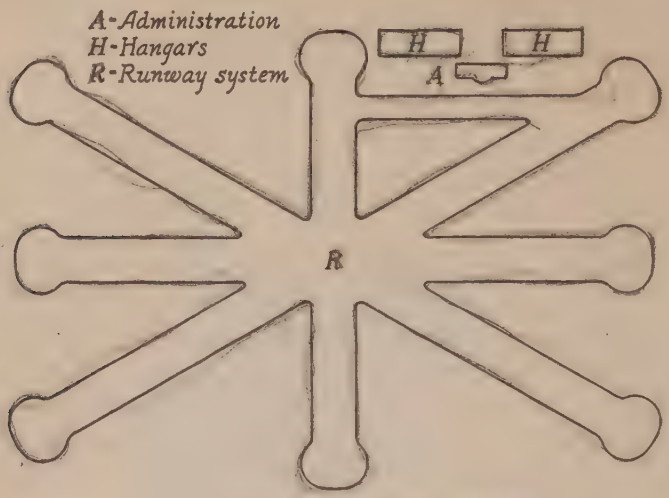


FIG. 42. An airport with its runways.

plane with the other. The engine quickly comes to full speed and the plane quickly gains velocity. (See step *A* in Figure 43.)

As the plane is gaining velocity, push gently forward on the stick (or wheel). This holds the elevator down. When the forward speed of the plane is such that the pressure of air is great enough on the underside of the elevator, it will lift the tail (*B*, Fig. 43).

When the plane has reached a level position, stop pushing forward on the stick. Let the plane gain a little more speed in the level position, rolling forward on two wheels. Then pull the stick gently backward (toward you). When the plane has gained flying speed, it will rise gently from the ground (*C*, Fig. 43), and you are off!

If you take off without the push forward that lifts the tail, the plane, because its nose is pointed up, tries to get off the ground, so to speak, before it has flying speed, and the effect is a bumping up and down until it reaches flying speed.

If you neglect to pull back on the stick after the plane

attains flying speed rolling on the ground, it will roll much farther than necessary before taking off.

If you try to lift the plane off the ground too soon — that is, if you pull back on the stick too soon while getting up speed on two wheels — the plane will rise a little, then sink to the ground again and bounce a few times before finally getting up flying speed.

In taking off it is important not to try to climb too steeply. After the plane has left the ground, give it time to get up full speed (*D*, Fig. 43), then climb gradually (*E*). Always go straight ahead at first because a turn slows down the plane and you need full power for climbing to get well over all possible obstructions beyond the end of the runway.

It goes without saying that you will practice take-offs and landings many times with an instructor before attempting to solo (fly by yourself). From twenty-five to fifty times may be enough practice in taking off.

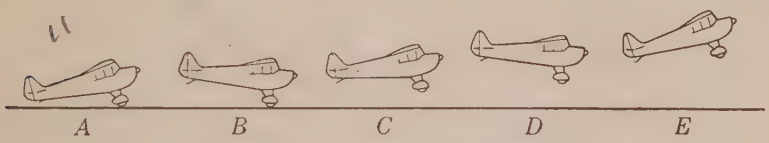


FIG. 43. The steps in taking off.

QUESTIONS

1. What is a pilot said to be doing when propelling the plane along the ground?
2. What is meant by "landing gear"? Specify the parts.
3. In what ways may the tail of a plane be supported?
4. Is an airplane engine started with the throttle open or closed?
5. When an attendant, about to start an engine, says "Contact," what does the pilot do?
6. After starting the engine for the first time during a day, what does the pilot do before flying?
7. When taxiing a plane toward the north (one having a swivel

tail wheel), if the wind is from the east, does the plane tend to turn toward the right or toward the left?

8. When a plane is being taxied rapidly, does a given forward position of the right foot cause greater or less tendency to yaw than when the plane is being taxied slowly?
9. Which is the easier to steer in a stiff cross breeze, a plane with a swivel tail wheel or one with a steerable tail wheel? Why?
10. Why does a pilot take off, if possible, directly into the wind?
11. What is a wind sock? How does it function?
12. What are the steps in taking off? Describe them.
13. What may happen if in a take-off you pull the stick back too soon? too late?
14. How many brakes are there on a plane? How are they operated?
15. What does the pilot do before saying "Contact" when preparing to take off?
16. At about what minimum temperature should the oil be before taking off — 100°, 200°, or 300° — in a light plane?

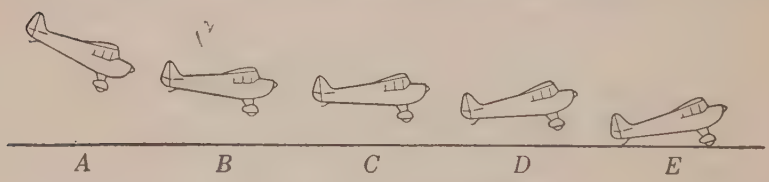


FIG. 44. The steps in landing.

6

LANDING

FLYING the plane when it is once in the air is the easiest part of flying. Next easiest is taking off. Landing is the hardest of all.

Briefly, the steps in landing are as follows:

1. Choose a runway pointing upwind.
2. Get the plane pointing directly down the runway.
3. Close the throttle; that is, shut off the power, or almost shut it off, to let the plane glide.
4. Be careful not to overshoot or undershoot the end of the runway.
5. Start to level off as you approach the ground (See steps *A* and *B* in Fig. 44 on the opposite page).
6. Level the plane, slightly above ground (*C*).
7. Hold the plane above ground while it loses flying speed.
8. Bring the nose up and tail down to landing attitude (*D*).
9. Let the plane sink to the ground for a three-point landing (*E*).
10. Hold the tail down by holding the stick back (toward you) and steer the plane, keeping it in the runway until it comes to rest.

Choosing the runway

It is customary, before landing in an airport, to circle the field at least once. This gives you time to look the place over and see that no plane is about to take off. It gives other pilots a chance to see that you are going to land. It gives you a chance to look at the wind sock and see which way the wind is blowing (it may have changed direction since you

took off), and to select the proper runway. Be sure to land upwind.

Gliding to the runway

When you have the plane pointing directly along the proper runway, close the throttle (shut off the power) and point the nose slightly downward, into the gliding position. The engine will idle; it will not stop entirely. The plane will glide down at a slight angle, propelled by gravity.

It is important to realize that a plane will stall when gliding just as easily as when flying, if not more easily, unless the necessary speed is kept up. You must be very careful, therefore, to keep the nose of the plane pointed down. If you get to flying level, the plane may lose gliding speed and stall before you realize what has happened.

It is well to glance at the air-speed indicator from time to time whenever you are gliding, until you have become thoroughly accustomed to gliding and maintain gliding speed subconsciously. In light planes 60 miles an hour is usually a good gliding speed.

The yawing, pitching, and banking of the plane are done in the same way when gliding as when flying. That is, you yaw the plane with the foot pedals; you raise and lower the nose by pushing and pulling the stick; you bank to the right or left by moving the stick to the right or left.

You will quickly discover, when first gliding, that the controls handle quite differently in gliding from the way they handle in flying. The rush of air against the ailerons, rudder, and elevator is much less than when the plane is flying under power; therefore, the same movement of the stick or pedals produces much less movement of the plane. In other words, it takes more movement of the controls to produce the same effect in gliding as in flying with power. This means that you must learn an entirely separate set of control habits in order to steer the plane properly in the glide.

This being the case, it is well to practice gliding by itself for a while before attempting to land. On a slightly gusty day ask the instructor to let you go up to 3000 feet and glide down nearly to the airport. Give your whole thought to getting used to the controls as you glide. If you know that the instructor will land the plane for you, you will not be distracted. If the wind does not blow you off your course and give you practice in righting the plane, then practice turning the plane slightly from side to side as you glide in order to get the feel of the controls. Practice gliding first toward one point on the ground, then toward another and another, to gain skill in steering the plane in a glide.

Undershooting and overshooting

Part of the secret of skillful landing lies in knowing when you should start the glide, as you approach the airport. Obviously if you start gliding too far away from the airport, you will not reach it. This is called *undershooting*. In that case, as soon as you see that you "can't make it," you have to push in the throttle part way at least, to speed up the engine and fly the plane up closer to the field; then you start a new glide when you are close enough to glide into the airport.

If you start the glide too late in approaching the field, you may realize that you would be halfway across it before you could reach the ground. This is called *overshooting*. In such a case it may be necessary for you to "give it the gun," as we say (give the engine full power), and go on over the field, circle it again, and the next time start the glide farther away.

Leveling off

After you have become used to flying the plane in a glide and can keep it pointing down the runway without much thought, you are ready to practice leveling off.

Leveling a plane for landing is a little like parking a car by backing it. In parking a car you try to get the car parallel to the curb just at the time it reaches the curb. If you back in at too wide an angle, the rear tire bumps the curb and the front of the car still stands away from the curb. If you cut in too soon, the car is still some distance from the curb when you have brought the car up parallel to it.

So with landing a plane, you have to get the plane leveled off by the time it is still two or three feet off the ground.

If you reach the ground before you have leveled off, the plane dives into the ground and bumps the landing gear. If you level off too high above the ground, the plane eventually stalls and falls to the ground with a plop! (See Fig. 45.)

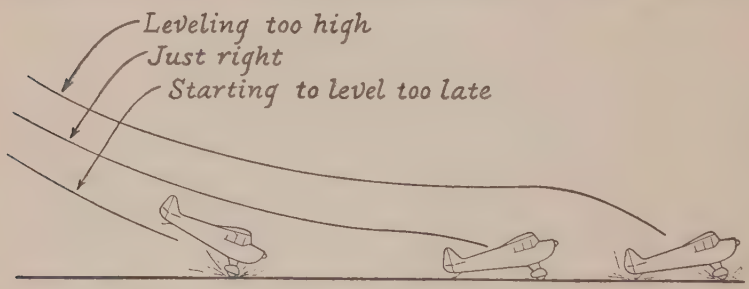


Fig. 45.

A skillful pilot can sometimes level off a few inches above ground, but it is not wise to try to do this regularly.

Losing speed

While skimming along with power off, two or three feet above the ground, the plane is gradually losing speed and approaching the stalling point. You must therefore be very alert. As you detect the slightest tendency for the plane to sink during this skimming, you try to overcome the tendency by gradually lifting the nose so as to hold the plane off the ground. We call it trying to lower the tail while still keeping the wheels off the ground.

Landing attitude

The gradual lowering of the tail continues at just the rate necessary to hold the plane above the ground until the plane is tipped up to the angle at which it stands on the ground. This is called the *landing attitude.*

Three-point landing

When the plane has reached the landing attitude while still flying level it is ready to stall, and when it stalls it will drop to the ground, landing on all three wheels. This is called a *three-point landing.*

An important part of learning to land consists in getting used to the controls so that you do not pull the nose up faster than you intend to or fail to lift it as much as you intend. These difficulties arise from not knowing the exact relation of amount of pull on the stick to amount of lift of the nose.

Timing

Learning to land properly consists chiefly in (1) learning to time the leveling of the plane so that it is level as it reaches the height of two or three feet from the ground, and (2) timing the lifting of the nose during the approach to stalling speed in order to hold the plane at a constant distance off the ground until it stalls and falls off to a three-point landing.

Where to look

One difficulty students have in landing lies in their not knowing where to look. You have the feeling that in order to keep the plane straight you must look out ahead; but it is difficult, looking that way, to judge how far you are from the ground. If you try looking down at the ground near the plane, it is hard to tell whether or not the plane is going straight in the direction in which you wish it to go.

One good way is to look back and forth from the distance

ahead to the ground near the plane so that you may be able to keep the plane straight and at the same time know approximately how far it is off the ground.

Another way is to look at the ground a few hundred feet in front of the plane and divide your attention between noticing whether or not the plane is veering to one side or the other and noticing how far you are above the ground.

Whatever method you use, it is important that you focus your eyes; do not just stare blankly ahead. Focus your eyes on some particular stone, clump of grass, or spot on the runway and shift your focus successively from one such spot to another. Remember that depth perception or judgment of distance is accomplished primarily by bifocal vision — focusing the two eyes on one object.

Nervous distraction

Another difficulty that students have is the inability to give full attention to what they are practicing, because of fear or anxiety. If you are worried while trying to level off, because you fear you will not know what to do with the plane when you have it landed and find it rushing along the ground at 50 miles an hour — possibly heading for a fence — this fear or anxiety distracts your attention from what you are trying to learn and makes the learning take much longer. It is possible to learn in one hour of concentrated effort, free from any distraction, what it would take four or five hours to learn otherwise — maybe ten hours.

If while learning to level off you find yourself being afraid you won't know what to do next, arrange with the instructor either to take over the controls after you have leveled off or else to let you go on up again without landing. Then you will have nothing to worry about while you are practicing the leveling off. When you have learned to level off satisfactorily and at the same time to give some thought to what comes after, you are ready to follow up with the landing.

Taxiing after landing

When the plane has finally settled to the ground on landing, it is still going very fast — maybe 50 miles an hour. That is no time to relax and feel that the landing is finished. You must "keep on flying the plane."

First, remember to hold back on the stick (or wheel) after landing to hold the tail down and to keep the plane from nosing over (tipping its tail up). Next, keep the plane steered in the direction in which you wish it to go (down the runway if you are landing on a runway), and keep the plane's wings level. After the plane has touched the ground you steer it and keep it level in exactly the same way as when flying.

If necessary to make a turn after landing, go ahead and turn. You turn the plane in the same way while taxiing rapidly as while flying — you bank it a little and push the proper pedal. That is why we say that you "keep on flying the plane."

The psychology of practice

Here are some psychological principles to follow in learning to fly (or in learning to do anything else, for that matter).

First of all, try to single out one skill at a time for practice. It is a great mistake to try to practice several things at once or in quick succession. You can't give full attention to one thing and at the same time be trying to think how you are going to do something else the next instant.

This means that you should not try to learn to do in succession all the things constituting a complete flight. Do not try at the outset to take off one moment, fly the plane the next, and then land the plane.

First learn to fly the plane in a straight line.

Next learn to fly the plane in a turn.

Next learn to taxi and take off. These two can be learned together, because you do not have to do them in quick succession. You may have to combine landing practice with take-off practice for economy. Otherwise it would be much better to practice take-offs and landings separately.

Before attempting to land a plane you should practice gliding separately, as explained above. Practice steering the plane in a glide, both in keeping it straight and in turning it.

If, while you are learning to level off, you are distracted by anxiety over the landing, let the instructor set the plane down the first few times so you can concentrate on the leveling process; then practice the landing also.

Of course you will not try to perfect each step in landing before going on to the next. The idea is to concentrate as far as possible on one thing at a time when just beginning to learn it. Then gradually put two or three things together.

Questions

1. Which is considered hardest, taking off, ordinary flying, or landing?
2. Why do we land upwind, if possible?
3. Can you name the steps in landing? What are they?
4. Does the pilot shut off the ignition when about to land?
5. Does it take more or less movement of the controls to steer a plane in a glide than in normal flight?
6. If a pilot sees he will undershoot the field, what should he do?
7. If a pilot sees that he will overshoot the field, what should he do?
8. What happens if a pilot levels off too soon? too late?
9. What is a three-point landing?
10. What does the pilot do with the stick just after landing? Why?

7

SIDESLIPPING

LET us suppose that the normal gliding angle of a given plane is such as to give one foot of descent for each 10 feet of forward glide. If you are about 1000 feet (measured on the field) from the spot at which you wish to land and if you are 100 feet up, you will be able to make a normal glide just to the spot. But if you are, say, 200 feet up, you will have to glide down 2 feet for every 10 feet of forward motion in order to make the spot. Pilots sometimes have need to glide thus more steeply than at the normal gliding angle. If you try to do this by merely pointing the nose lower, the plane quickly picks up speed and you may find yourself approaching the ground at a much greater speed than necessary in a normal glide.

The sideslip

It has been found possible to glide a plane partially sidewise as shown in Figure 46. This maneuver is called a *sideslip*. It enables the pilot to bring the plane down at a much steeper

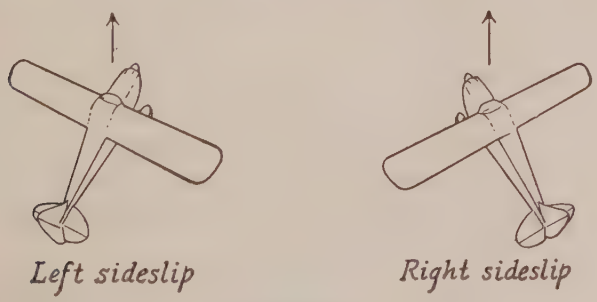


FIG. 46.

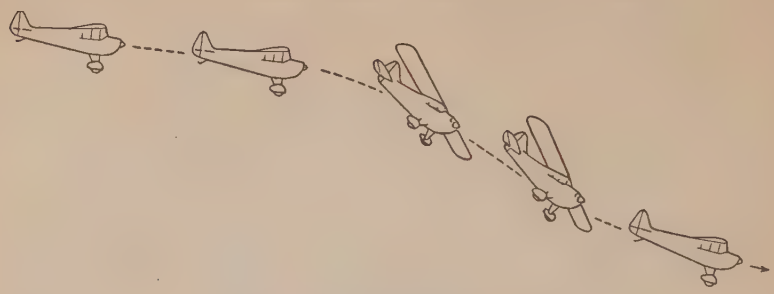


FIG. 47. A left sideslip, side view.

angle than is possible in a normal glide and yet does not require a greater speed than normal. (See Fig. 47.)

The sideslip is entered from a normal glide. Let us say you are gliding northward and wish to make a left sideslip, as in Figure 48. Gradually push the right rudder pedal part way forward and hold it there, and at the same time gradually push the stick part way to the left and hold it. The plane will assume an attitude pointing slightly east of north with the left wing down, it will glide northward more steeply, as in Figure 47, but at no greater speed than in the normal glide.

To increase the sideslip, push the rudder pedal farther forward and push the stick farther to the left. The plane will then point farther to the east, its wing will be lowered farther, and the plane will glide more steeply but still northward and only a little more rapidly than in a normal glide.

If the normal gliding angle of a plane happens to be 1 foot of descent for each 10 feet of forward glide, a sideslip may enable you to descend a distance up to, say, 2 feet for each 10 feet of forward glide, with but slight increase in speed. (It is possible to sideslip too steeply and hence gain speed the same as in a too steep glide.)

If the movements of rudder pedal and stick are properly coördinated, the plane will sideslip in the same direction

as that of the glide before the sideslip was entered, as shown in Figure 48.

A sideslip executed in the deliberate manner described above, and hence producing a slipping in a forward direction, is sometimes called a *forward slip*.

Landing straight ahead

You must never strike the ground with the nose pointing other than straight ahead — in the direction the plane is moving.

To right the plane (get it pointing straight ahead) after a sideslip, you merely release the pressure on the rudder pedal and stick, letting them come back to neutral. The plane will swing around and point in approximately the direction in which it has been slipping and continue to fly in the same direction, as shown in Figure 48.

If the plane is pointing down too steeply after releasing the pedal and stick, the nose should be lifted to give the plane its proper gliding angle.

Steering the sideslip

If, while in a left sideslip, you wish to direct the plane slightly to the right but to continue the slip, lift the left wing a moment, then lower it again. While the left wing is raised, the plane will turn slightly to the right.

If you wish, while in a left sideslip, to steer the plane slightly to the left, release the right rudder pedal a moment, then press it forward again. During the release the plane will swing slightly to the left.

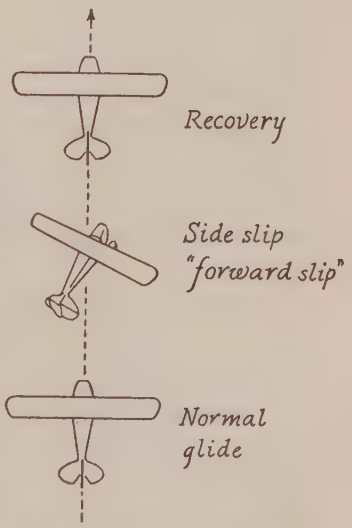


FIG. 48. A left sideslip, top view.

To enter a *right* sideslip, and to steer the plane in a right sideslip, you need merely to reverse the control movements that are used for a left sideslip.

Effect of sideslip on controls

In a sideslip to the left, for example, the plane yaws only a certain distance and then stops even though the rudder pedal is held forward. The reason is that — because of the sideward motion of the plane — the pressure of air on the left side of the fin and fuselage becomes great enough to counteract the yawing force of the air on the right side of the rudder. The *fin* is the stationary vertical tail surface.

The reason the plane does not continue to roll to the left in a left sideslip with stick to the left is that — because of the sideward motion of the plane — the air pressure under the low wing is greater than that under the high wing which is shielded by the fuselage, and this air pressure finally counterbalances the rolling effect of the ailerons.

What slows the plane?

Obviously, when a plane is moving sidewise through the air it is presenting the side of the fuselage to the air to a large extent and hence the air offers more resistance than otherwise. This is what slows the plane and enables it to glide steeply without gaining speed.

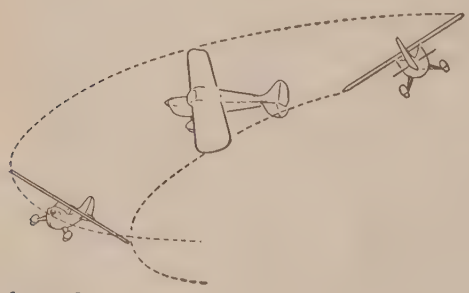


FIG. 49. The slipping turn.

Sideslipping without rudder control

In Chapter 3 we spoke about a plane slipping in a turn when there was too much banking for the radius of turn. There is a difference between this involuntary slipping and the sideslipping done deliberately in order to steepen a glide. The first kind of slipping is without rudder control; the second kind is with rudder control.

If you are gliding and bank the plane to the left, for example, without rudder control (that is, without pressing the right rudder forward), the plane will not sideslip in the useful manner described above but will begin to slip to the left and will gradually curve off to the left into a dive.

Slipping turn

Sometimes a pilot has need to glide steeply and to make a turn at the same time (Fig. 49). It is perhaps easiest to do this maneuver by beginning first on the normal turn. In a glide a normal turn is executed the same as in level flying — by banking with slight yaw and pitch. Having started the normal turn, say to the left, lower the left wing a little more and press the right rudder a little (that is, release the left rudder slightly) and the plane will sideslip gently while in the turn. What you have done, then, is merely to superimpose the sideslip-control movements on the normal turn control movements.

To come out of a slipping turn you may, if you wish, first restore the turn to normal by releasing the extra pressure on the rudder and stick, then come out of the normal turn as usual.

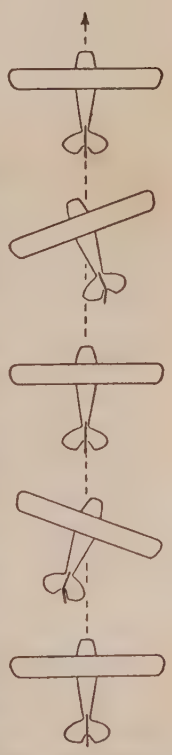


FIG. 50. Fish-tailing.

Fishtailing

Fishtailing is a term used to describe a maneuver sometimes used to slow down forward speed. It consists of a series of skids, first to one side and then to the other (Fig. 50). The movement is produced by yawing first to one side and then to the other, without banking. Fishtailing is not as effective for slowing down a steep glide as the sideslip because in a sense it is merely a succession of alternate sideslips which intermittently slow the plane, whereas the sideslip continuously holds the plane back.

Need for sideslipping

Sideslipping need not be used in normal landing. Indeed, if so used it indicates that the pilot has misjudged his approach. As explained in Chapter 9, the need for sideslipping is principally in the case of a forced landing in a small field because of engine failure, or under stress of weather or poor visibility. It is quite necessary, therefore, that the pilot be able to sideslip with confidence and good control.

Questions

1. What does a pilot do to glide more steeply without increasing his speed?
2. Describe a sideslip.
3. How does a pilot put a plane in a sideslip to the left?
4. How does a pilot recover from a sideslip to the left?
5. Is it proper to land while sideslipping?
6. How can a pilot steer a right sideslip to the right? to the left?
7. Why can a plane glide more steeply in a sideslip without increased speed?
8. Is it possible to turn and slip at the same time?
9. What is fishtailing?
10. When may a sideslip be needed?

8

STALLING — SPINNING — STEEP TURNS

THERE are special maneuvers that the pilot should understand and be able to execute, partly for safety in cases of emergency and partly for the value of the practice in developing coördination and general skill in manipulating a plane. Among these are stalling and recovery, spinning and recovery, steep turns, spirals, and spot landing or precision landing.

STALLING

Stalling the plane

A plane is said to *stall* when it loses flying speed. When a plane stalls and until it regains flying speed, it ceases to be able to sustain itself in level flight and begins to fall to the ground.

The prime requisite for recovering from a stall is to regain flying speed, and to regain flying speed the plane must nose down.

Planes differ in their stalling characteristics. Some planes when stalled act as if they were in unstable equilibrium at the moment of stalling and "fall off" to one side or the other with a spin. That is, one wing drops (presumably the wing that stalled first) and the plane spins around a vertical axis.

Other planes are designed so that in a stall the plane will ordinarily merely nose down — fall forward, so to speak, and go into a dive. Such planes are safer for the beginner, and most training planes are of this type.

If the plane is one which tends to nose down automatically when stalled, the plane itself takes care of the prime requisite

for recovering from a stall. A nosed-down plane goes into a dive; that is, it quickly gains speed when headed downward. The maneuver, therefore, for recovering from the stall and subsequent dive is merely to restore the plane to level flight.

Most planes in a dive tend gradually to level off automatically; but if a plane is left to itself, this leveling is usually so gradual that the plane will get into a too rapid dive and lose a great deal of altitude before it levels off. It is necessary, therefore, that the pilot himself level off the plane as soon as it regains flying speed as the result of nosing down after stalling.

In the case of a plane that does not automatically nose down, the pilot must detect the stall at once and push the nose down promptly to pick up flying speed, and then level off. The pilot detects the stall by the weakening of the controls; that is, the usual movements of stick and rudder produce less than the usual effect on the movement of the plane.

The danger of stalling

If the pilot senses promptly that his plane has stalled when it does stall, and sees to it that the plane noses down at once to gain flying speed, and if he levels off promptly after gaining flying speed, no harm need ever result from the stall — that is, so long as the plane is high enough when it stalls so that it can be nosed down and leveled off before striking the ground. The danger of a stall lies wholly in being too close to the ground for recovery when the stall occurs.

The need to practice stalling

It is desirable that the pilot should practice deliberately stalling the plane and recovering. He must (1) learn to recognize a stall promptly, before it may result in a spin,

(2) learn not to get panicky, (3) learn to do automatically the things necessary to recovery, and (4) realize the loss of altitude necessary in recovering from a stall and never do anything near the ground that could possibly result in a stall. Obviously, all practice in stalling is done with plenty of altitude — 3000 feet or more.

A plane may stall either with power off as when gliding, or with power on as in ordinary flight. It is well, therefore, to practice stalling the plane both with and without power.

Power-off stall

To stall a training plane with power off, close the throttle, put the plane into a glide, then gradually lift the nose until the plane is level and try to hold it level or even put it into a climb. In a few seconds the plane will stall. The plane will stall more quickly, of course, in a climb than when level. To recover, nose down promptly and as soon as flying speed is regained resume the normal glide (Fig. 51). As explained above, when a plane stalls, the nose drops, but not enough to enable the plane to regain flying speed promptly.

Power-on stall

To stall a plane with power on, gradually pull the nose up to a steep angle, say 45° with the horizontal. In a few seconds the plane will quiver and stall. To recover, push the nose down promptly and as soon as flying speed is regained resume level flight (Fig. 52).

SPINNING

The tailspin

Most planes have the tendency when stalled under some conditions to go into a *spin*. The spin is often called a "tail-spin," but this term may be somewhat misleading, since the plane spins with its nose down and tail up.

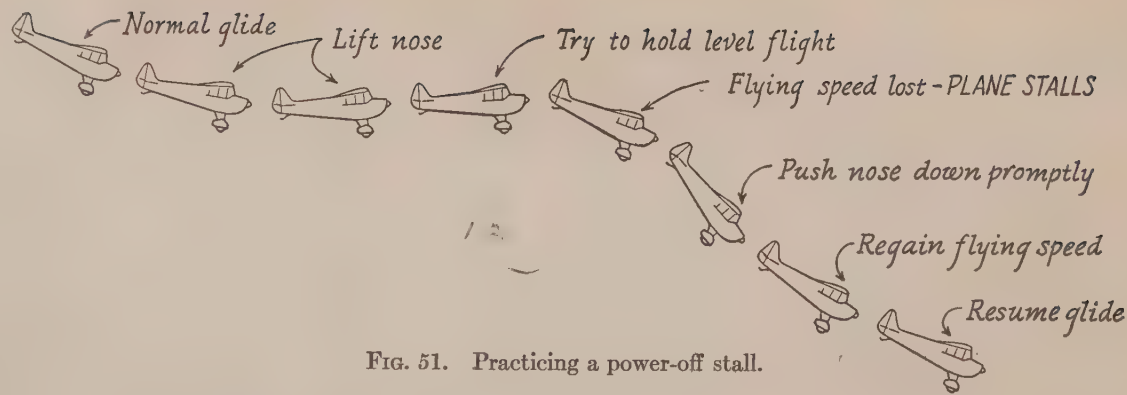


FIG. 51. Practicing a power-off stall.

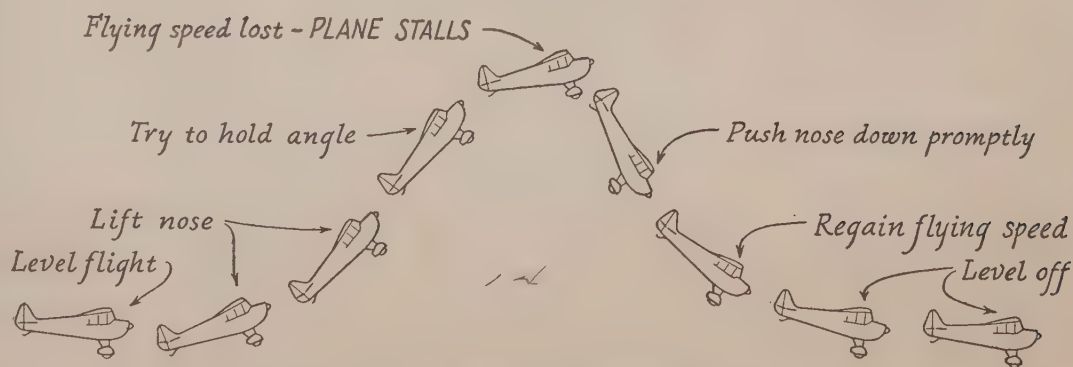


FIG. 52. Practicing a power-on stall.

When a plane spins it is rapidly sinking (though usually sinking at a uniform rate) and it is turning with a very short radius around a vertical axis, as shown in Figure 53. The plane may be turning so as to revolve around the vertical axis perhaps once in every two seconds.

Cause of a spin

To understand the cause of a spin, you must understand what is meant by angle of attack, forward component of gravity, etc. These matters are explained in Part II, and the cause of a spin is given at the end of Chapter 12.

Going into a spin

To put a plane into a spin, you begin by stalling it. Spins are usually practiced with power off. To stall the plane with power off, try to hold the plane level; in a few seconds it will stall, as explained above.

If the plane is a training plane which tends in an ordinary stall to nose down more or less straight, you can make it spin to the right by pressing "full right rudder" at the moment of stalling. This produces a slight yaw to the right and thus causes the right wing to lose flying speed and stall. The left wing is still able to move forward and cause the plane to spin.

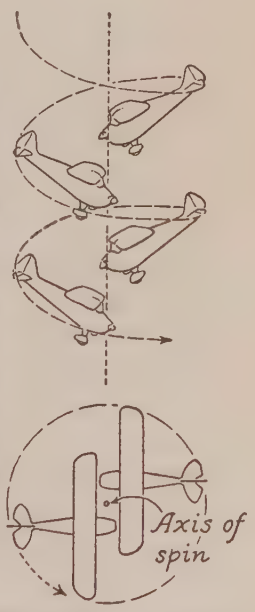


Fig. 53. A tailspin. Side view (upper drawing); top view (lower drawing).

The cause of a spin is explained more fully on page 132.

With stick still held fully back and with full right rudder the plane will spin to the right. With stick fully back and full left rudder the plane will spin to the left.

Recovering from the spin

If the plane is of the training type, it will stop spinning if the rudder is allowed to return to neutral. In other planes it may be necessary to press full opposite rudder to stop the spin.

At the instant the spinning is stopped with the rudder the stick is released, and pushed down if necessary, so that the plane will nose down promptly and not stall again. Then, in a moment, when flying speed is regained the plane is returned to the normal glide or to level flight.

Need to practice spinning

Since the spin is such an unusual action of the plane, if a pilot got into a spin without having previously experienced one, he would very probably become panicky and have no idea how to recover.

It is important, therefore, that the pilot practice deliberately going into a spin, both right and left, and recovering. He will then (1) recognize a spin when he gets into one unintentionally, (2) not get panicky, and (3) know how to recover promptly.

If a pilot spins a plane with plenty of altitude and knows how to recover, there is no particular danger in a spin.

The Civil Aeronautics Board inspector in giving a flight test usually requires the candidate for a private pilot certificate [1] to recover the plane after just two turns of a spin have been made. Ability to do this assures the inspector that the pilot was in full control of the situation and knew exactly what he was doing at all times.

Incidentally, the law requires that no spin may be performed intentionally unless all occupants of the plane are equipped with parachutes.

[1] See Chapter 41 on requirements for a pilot certificate.

STEEP TURNS

The steep banking turn

There are occasions in which a sharp turn needs to be made. The sharpest turn that can be made continuously is one in which the banking is about 70° with the horizontal (Fig. 54). A steeper bank than this, if continued, will probably result in a stall — it slows the plane down too much. A plane can fly with the wings vertical in the course of a turn, but only momentarily.

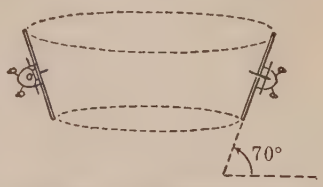


FIG. 54. The steep banking turn.

It is important that the pilot practice steep turns, since the coördination of the controls for yawing, pitching, and banking is quite different from that for shallow turns, as has been explained previously.

To execute a steep turn (say 70°), it is necessary to have somewhat more power than necessary for cruising speed. When the plane has been given additional power, the steep turn is entered the same as a shallow turn — by banking with a proper combination of yaw and pitch to maintain altitude and to keep the plane from skidding or slipping. Gradually bank the plane more and more until the turn is as steep as desired.

Not only does the plane tend to stall if pulled into a steeper turn than the 70-degree bank turn, but also the pitching (pull-up of the plane's nose) for such a steep turn becomes so great that it causes uncomfortable drag on the pilot's stomach and other organs.

When a 70-degree bank is reached, hardly any yawing is necessary, but the pitching must be watched carefully. Too little pitching results in slipping toward the center of the turn and losing altitude. Too much pitching is very likely to result in stalling.

Recovery from a steep turn is accomplished the same as recovery from a shallow turn, except that the emphasis is on rolling the plane back to the level attitude. The stick is gradually released from its backward position and the rudder pedals are hardly moved at all.

Mushing (Pancaking)

A maneuver which is possible with a plane but which is ordinarily avoided altogether as being very dangerous is one known as *mushing* or *pancaking* (Fig. 55). Thus, it is possible for some planes to approach the ground in an attitude which we might describe as halfway between a glide and a stall. If we begin with a normal glide and, pulling back on

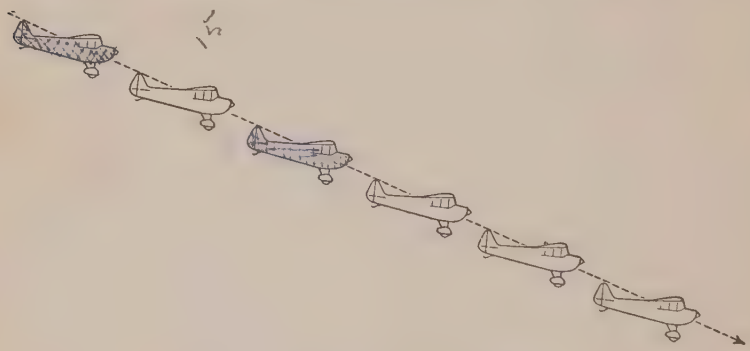


FIG. 55. Mushing or pancaking.

the stick a little, lift the nose part way toward level, the plane will sink even more rapidly than in the glide. If this sinking is continued, the plane will strike the ground nearly level but with such speed and force as seriously to damage the plane and injure the occupants. Moreover, a mushing plane is very unstable and is likely to stall and fall off to the side at any moment.

Mushing is not quite so dangerous in a training plane as in some other types, but nothing is gained under any ordinary

circumstances by mushing. Sideslipping is much safer for losing altitude in a short space without excessive speed; hence mushing is to be avoided altogether when the plane is anywhere near the ground.

Ground looping

When a plane is improperly landed, it sometimes goes into a *ground loop;* that is, it spins around rather violently in a small circle on the ground. A ground loop happens usually when a pilot inadvertently applies too much brake to one wheel or otherwise gives the plane an initial tendency to turn suddenly to one side or the other while taxiing rapidly. When once started, a plane tends to continue to ground loop until its energy is spent, even though the brake is released. However, in such a case there is an extra lifting force under the outside wing, because of its greater speed, which tends to prevent the plane from tipping over. A ground loop may be stopped, or at least reduced in violence, by applying full opposite rudder and giving a blast from the propeller promptly when the ground loop starts.

Questions

1. What is stalling?
2. What does the nose of an ordinary training plane do when a plane stalls? What happens when some other planes stall?
3. Why should you practice stalls?
4. How does a pilot stall a plane with power off? with power on?
5. What is a tailspin?
6. How does the pilot put the plane into a spin?
7. How does he recover from a spin?
8. Why should you practice spins?
9. Can a plane fly a circle with an 80-degree bank?
10. What difficulties does a student pilot experience in steep turns?
11. What is mushing or pancaking?
12. Is mushing often used in landing?

9

SPOT LANDING — SPIRALS — ACROBATICS

BEFORE a pilot can fly with reasonable safety, he must be able to set the plane down in a field of moderate size in an emergency. This requires his being able to bring the plane to a landing close to the near edge of the field, so that he can use most of the length of the field in bringing the plane to a stop.

Spot landing

Practice for such emergency landing is secured by making *spot landings*, or precision landings, at an airport. There you make your spot landing just over a given line representing the near edge of an emergency field.

The difficulty all beginners have is in either overshooting or undershooting the line. *Overshooting* means coming in so high that if the field were a small emergency field, the plane would still be skimming the ground at considerable speed when the far side of the field was reached and it would perhaps crash into trees. *Undershooting* means approaching the line so low that if the field were a small emergency field,

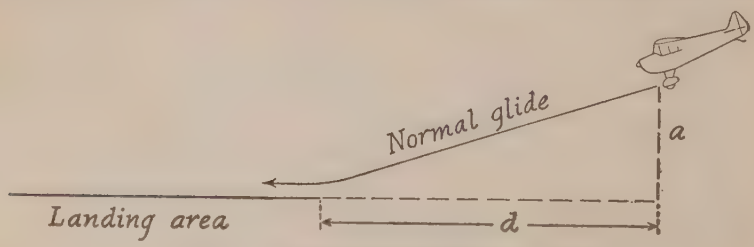


FIG. 56. Approaching the field in a glide.

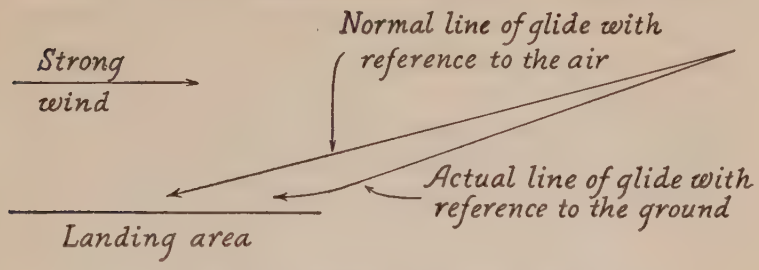


FIG. 57. Landing in a strong wind.

it would not be reached before the plane struck the ground or surrounding obstructions.

The pilot must learn to judge the proper distance (*d*) (Fig. 56) from which to approach the field at the altitude (*a*) so that he will just reach the edge of the landing area as his plane is about to land.

The pilot must gauge the wind velocity, since the stronger the wind the less distance (*d*) he can allow, and the less the wind the greater distance (*d*) he must allow.

Obviously, the stronger the wind the more the plane is blown away from the field while the gliding is being done and the steeper the actual line of glide will be even though the gliding angle with reference to the air remains the same. (See Fig. 57.)

Actually the pilot always approaches the landing area from a point which would normally carry him a little way past the point at which he wishes to land (as shown in Figure 58), and

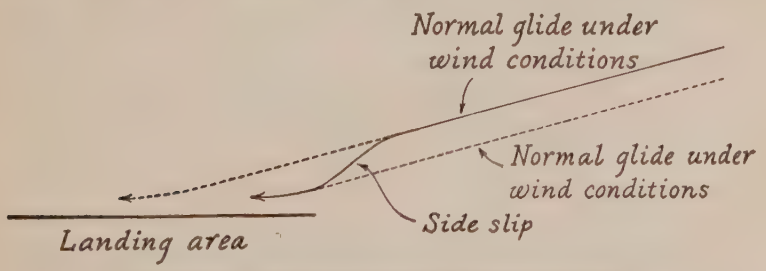


FIG. 58. Losing excess altitude by a sideslip.

when he is sure he has a little altitude to spare he resorts to the sideslip to lose the excess altitude and to land just over the edge of the landing area.

The sideslip is useful also when it is necessary to come into a field steeply over a fence or trees.

Essing

An alternative to sideslipping for losing excess altitude is "essing" (S-ing); that is, describing a letter "S," as shown in Figure 59, so as to make the actual glide longer than the straight-line distance to the edge of the field. Obviously you must be careful to do all your essing well above ground — do not leave any final turn to be made near the ground — and you must pay particular attention to maintaining flying speed during all essing turns.

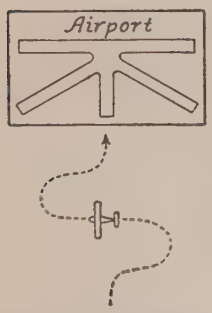


FIG. 59. Losing excess altitude by essing.

Judgment

Skill in judging the distance from a landing field at which to begin the glide is something that a pilot must acquire more or less by himself. It cannot be taught but comes only with practice. Some pilots seem deficient in the capacity to learn this skill and gain it with difficulty or not at all. The skill consists principally in being able to keep an eye on the spot on the field at which you wish to land and in knowing when the angle your line of sight makes with the ground becomes about equal to the gliding angle of your plane. That is when you should straighten the glide and head for the spot.

Slipping-turn

It is possible even to combine both the sideslip and essing; that is, to sideslip the plane even during a turn of the "S."

To sideslip in a turn, as previously explained, the pilot merely gives a little more bank than necessary for the turn and a little less rudder than necessary.

The more skill the pilot has at essing and sideslipping, the higher he may approach an emergency landing field and in that way be in less danger of getting "caught short" on account of strong wind.

SPIRALS AND ACROBATICS

Spirals

It is common practice to approach a landing field in a flight path called a *spiral.* A spiral is a flight path of the form called a *helix* [1] (Fig. 60). If it is desired to descend through a break in the clouds or to land from a considerable altitude on a spot directly below the plane, a spiral is commonly used.

Fig. 60. The spiral.

The spiral, usually done with power off, is merely a gliding turn continued to make several complete turns, gradually descending.

Practice is required to do a "tight spiral" without stalling, and also to spiral over a fixed spot when the wind is blowing, without drifting away.

In a light plane it is possible to make four or five complete turns while spiraling down 1000 feet — 200 to 250 feet of altitude being lost in each turn. A transport plane may require 1500 feet of altitude for one turn.

Accurate spirals are required in the test for private pilot certificate in connection with spot landings.

[1] The term "spiral" as commonly used refers sometimes to the shape of a coiled watch spring and sometimes to the shape of a corkscrew. The term "helix" refers only to the shape of a corkscrew. In aviation the term "spiral" refers to the corkscrew or helix type of spiral.

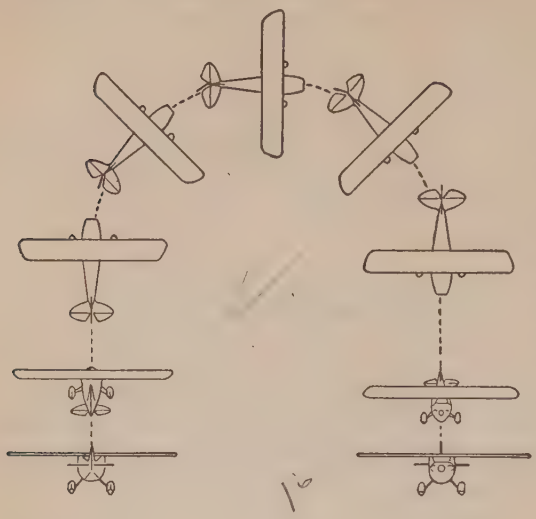


FIG. 61. The wing-over. In this figure the wing over is shown beginning at the left. It may be executed also with a turn in the opposite direction.

Acrobatics

Practicing stalls and spins and steep turns is classed as *acrobatics*. However, there are other maneuvers of a more definite acrobatic character which pilots engage in, partly to develop coördination and partly for the pure fun of it. These will be mentioned only briefly.

The *wing over* is perhaps the easiest acrobatic maneuver for a private pilot to learn (Fig. 61). Let us say the plane is flying north. The wing over consists of pulling the plane up to a steep climb (zooming), then tipping the nose to the east, say, so that at the top of the maneuver the plane is on edge (wings vertical) with the nose headed east. Then the plane is righted with a further turn to the south.

The *normal loop* is an upward-pitching vertical loop, as shown in Figure 62. It is entered from normal flight attitude with excess speed and is a rather simple maneuver.

The *inverted loop* is one in which the plane pitches downward, as shown in Figure 63. It is much more difficult than the normal loop.

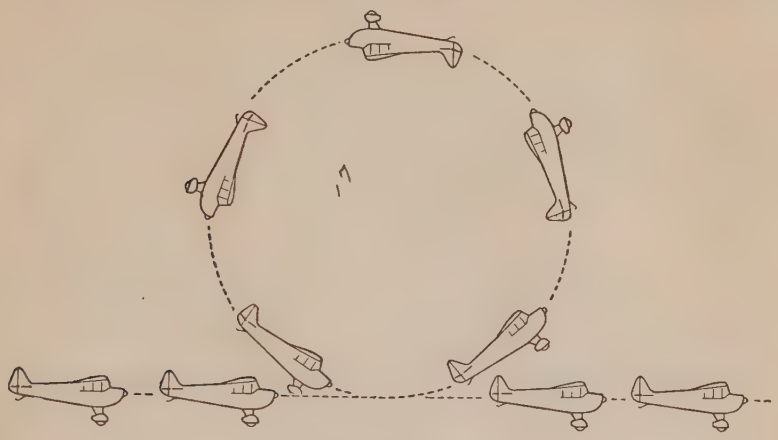


FIG. 62. The normal loop.

The *slow roll* (sometimes called the "barrel roll") is a maneuver in which the plane makes a complete turn on its longitudinal axis, as shown in Figure 64. The plane begins right side up, turns on its side, then on its back, then on the other side, and then is righted — all in one motion while moving straight ahead. Of course the roll may be executed either to the right or to the left.

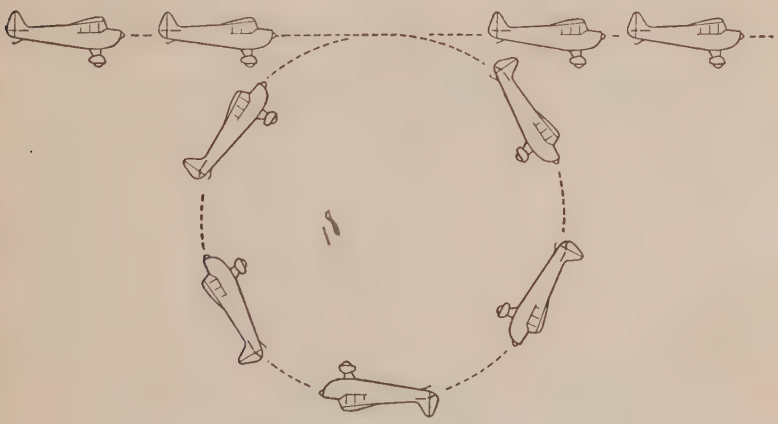


FIG. 63. The inverted loop, or outside loop.

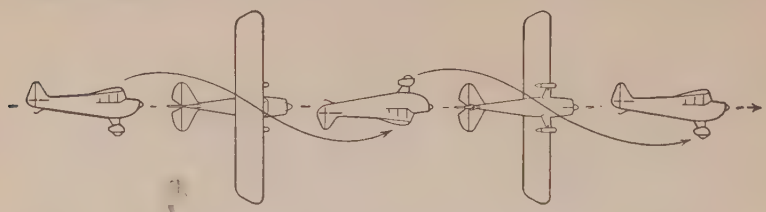


FIG. 64. The roll.

There are many combinations of these basic maneuvers, the most common of which, perhaps, is the Immelmann turn, named after the pilot who invented it.

The *Immelmann turn* (Fig. 65) is a half normal loop combined with a half roll. The half loop places the plane in an upside-down attitude, and instead of continuing the loop the plane is righted by the second half of the *roll*.

Among various possible combinations of loop and roll are the following:

Half normal loop — half roll (Immelmann)
Half inverted loop — half roll
Half roll — half normal loop
Half roll — normal loop — half roll

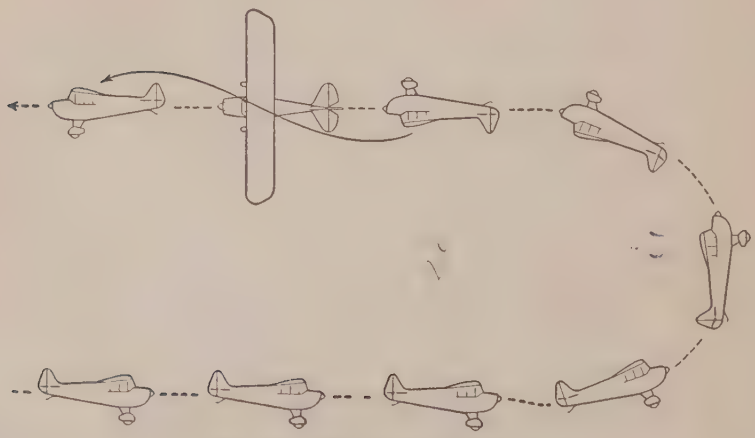


FIG. 65. The Immelmann turn.

The *Chandelle* is a maneuver which is most easily described by saying that it is virtually an Immelmann turn executed not in a vertical plane but in an inclined plane — say at 45°. The plane makes a half loop in an inclined plane, then is righted at the higher altitude. The Chandelle may be of any degree of steepness between a steep-banked level turn and the Immelmann turn.

Questions

1. What is spot landing?
2. Why should you practice spot landing?
3. What difficulties may a pilot encounter in a forced landing?
4. What is essing?
5. What is a spiral?
6. About how many turns can a light plane make in descending 1000 feet?
7. Describe a wing over.
8. Describe a normal loop.
9. Describe a roll.
10. Describe an Immelmann turn.
11. Describe a Chandelle.

10

CROSSWIND TAKE-OFFS AND LANDINGS

THERE are occasions in which it is necessary to take off or land crosswind (not directly upwind). In an emergency a pilot may find it necessary to land on a highway or a beach which may not point in the direction from which the wind is blowing. Moreover, some airports do not provide long runways in all directions.

For these and other reasons it is important that the pilot should know how to take off and land crosswind.

Crosswind take-offs and especially crosswind landings are dangerous in a high wind. In a wind of any velocity a crosswind take-off or landing is more difficult and requires more skill than one directly into the wind. In a light wind, crosswind take-offs and landings can be made with comparative safety.

Crabbing

If a plane is flying with its nose pointing directly north and there is a wind blowing from the east, the plane does not move over the ground in a path pointing to the north. In that case the path over the ground points somewhat west of north. This is because the plane drifts toward the west with the wind while traveling north through the air. This fact is explained more fully at the beginning of Part III, in connection with air navigation.

What you need to understand here is that because of this drifting of the plane with the wind it moves partially sidewise over the ground. This partial-sidewise movement over the ground is called *crabbing*. (Some crabs walk sidewise.)

A plane crabs to some extent if the wind is blowing in any direction other than in direct line with the way in which the plane is pointing.

Requirements for crosswind landing

First let us discuss *landing* crosswind. A landing of any kind requires that at the moment the wheels touch the ground they be pointing in the direction in which the plane is moving; that is, since the landing wheels on a conventional plane point in a fixed direction parallel to the long axis of the plane, to make a crosswind landing the plane must be pointed in the direction in which it is moving with reference to the ground at the instant the wheels touch the ground.

Because of crabbing, if a plane is flying directly northward toward a north-south runway and the wind is blowing from the right (east), the plane is headed to the east of north, as shown in Figure 66. If the plane is landed while pointing off to the right in this manner, the wheels will strike sidewise and cause great strain on the landing gear and probable damage.

As explained, in order that the wheels shall point in the

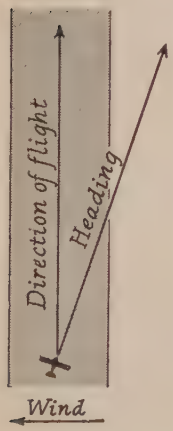


Fig. 66.

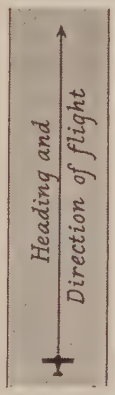


Fig. 67.

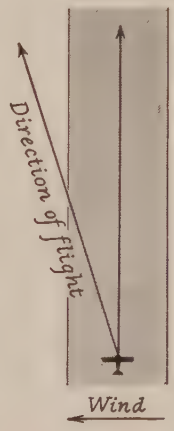


Fig. 68.

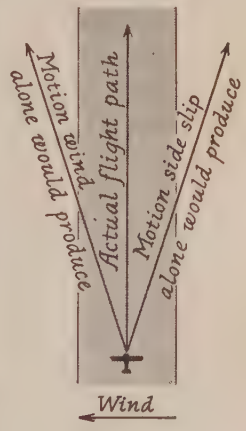


Fig. 69.

direction in which the plane will move on the ground when it lands, the plane must touch the ground *pointing* in the direction it is *moving*, as shown in Figure 67. If a plane is pointing directly down the runway, as shown in Figure 67, and the wind is blowing from the right side, the plane will be drifting to the left, as shown in Figure 68. In that case the plane will not even land on the runway, and besides it will strike the ground sidewise.

It is necessary, therefore, after getting the plane pointed down the runway, as shown in Figure 67, to keep it from drifting to the side (left), and we do this by means of a sideslip. That is, while the plane is drifting to the left we sideslip to the right just enough to overcome the drift and hold the plane on its course down the runway.

We have already learned (Chapter 7) how to slip a plane to one side. To slip a plane to the right, as necessary in this case, we use left rudder and right aileron. That is, we fly the plane with the right wing down but prevent a right turn by pushing down on the left rudder.

If it were not for the wind, the plane would then slip to the right and travel in a direction east of north, as shown in Figure 69. But this motion to the right with reference to the air is made just equal to the motion to the left produced by the wind, and the result is that the plane proceeds down the runway pointing in the direction it is moving; and when the wheels strike the ground they roll forward without strain.

Of course, the plane may be flying with its right wing down as it touches the ground and the plane may land first on one wheel, but the other wheel will come down promptly as the plane loses lift and settles into a level position.

To land with the wind from the left, we drop the left wing and hold the plane straight with right rudder.

In addition to this sideslipping to counteract drift, we must superimpose whatever other control motions are necessary to guide the plane in the usual manner.

This sideslipping is necessary in the case of any appreciable cross wind — one which would normally drift the plane off the line of the runway — regardless of the direction from which the wind is blowing. The more nearly the wind direction is to a line 90° from the direction of landing, the more slipping is needed; and the stronger the wind, the more slipping is needed.

Ordinarily if the wind velocity is over 15 to 20 miles an hour, it will not be safe to attempt a crosswind landing at 90° to the wind. The gustier the wind, the more dangerous is the crosswind landing.

Obviously a crosswind landing requires a certain amount of crosswind taxiing.

Crosswind taxiing

In taxiing northward with the wind from the east, we find that the plane has a tendency to turn to the right (into the wind), as explained in Chapter 5. To counteract this weather-vane tendency we put a little extra pressure on the left pedal so that the rudder will tend to turn the plane toward the left, and we push the stick a little to the right to give the plane a tendency to tip toward the right.

Note that for a wind coming from the right, left rudder and right aileron are the same control motions that we used in a crosswind landing with wind from the right.

Crosswind take-offs

A take-off begins with a fast taxi; it follows, therefore, that for the first part of a crosswind take-off with wind from the right we put extra pressure on the left pedal and hold the stick to the right.

As the plane leaves the ground it may be kept pointing straight down the runway by the same sideslipping procedure that is used in the crosswind landing; that is, by continuing

to hold extra pressure on the left pedal and lowering the right wing.

After the plane is safely in the air, it is not necessary to keep it pointed in the direction of the runway. The plane may then be leveled and flown in the normal manner with the nose pointing to the right of the runway; that is, crabbing to the right.

Obviously, for a wind from the left just the opposite control movements are used; namely, right pedal and left aileron (stick to left).

As the plane gains speed while taxiing in a take-off, less and less crosswind control becomes necessary. As a plane slows down in taxiing after a crosswind landing, more and more crosswind control becomes necessary.

Questions

1. What is the danger in a crosswind landing?
2. What method is used to overcome drift so as to stay on a line with the runway in a crosswind landing?
3. How is a plane put into a sideslip to overcome a drifting to the left?
4. How does the use of controls in crosswind taxiing compare with the use of controls in crosswind landing?
5. How does a plane take off in a cross wind?

PART II

Aerodynamics

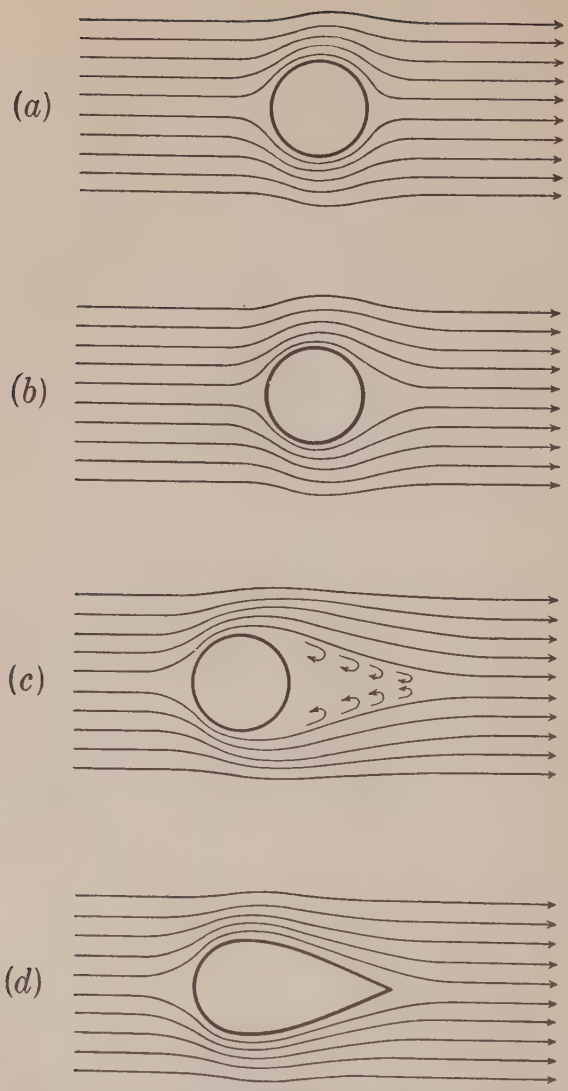


FIG. 70. Streamlines around a sphere (*a*, *b*, and *c*), and a streamlined body (*d*).

11

AIRFOILS AND STREAMLINES

IN Chapter 1 you were given a simple explanation of what holds a plane in the air during flight. Now it is time to go into the matter more deeply and consider all the factors contributing to what is known as *lift*. This involves a study of airfoils and streamlines.

Airfoils

An airfoil is any structure around which air flows in a manner that is useful in flight. The airfoils of an airplane which receive most consideration are the wings. Next in importance is the propeller, whose blades are airfoils just as truly as are the wings. Less important airfoils are the tail surfaces and the fuselage. Technically, we may say that an *airfoil* is a structure designed to produce a useful aerodynamic force.

Resistance to airflow

The resistance of an object to the flow of air around it is in part owing to the tendency of air to adhere to the object; but it is often, also, in large part owing to variations in air pressure.

Streamlines

If a sphere is placed in a moderate flow of air, the air flows around the sphere somewhat in the manner shown in Figure 70 (*a*).

The paths of the air particles as they flow past an object are called *streamlines*. As the speed of the air increases, the air

must make the turns in front of the sphere more rapidly; and the increased momentum of the air causes greater pressure on the front of the sphere.

Also as the speed of the air increases, the pressure of the surrounding air becomes less able to push the streamlines together promptly behind the sphere. Hence those streamlines draw away from the sphere somewhat as shown in Figure 70 (*b*).

This drawing away of the streamlines in the rear of the sphere tends to cause a partial vacuum in the space directly behind the center of the sphere, and the resultant reduced pressure behind the sphere together with the increased pressure in front causes the increased resistance of the sphere to the flow of air.

Burbling

As the speed of the air is increased still more, the streamlines become drawn so far apart as to leave a wide space directly behind the sphere, as shown in Figure 70 (*c*). This is called *separation*.

The air from the nearest streamlines *burbles* into this space, and disturbs the smooth flow of air past the sphere so much as greatly to increase the resistance of the air. We might say that the flowing air is now resisted both by the object and by the burbling air.

It has been found, however, that if the sphere is built out to a point in the manner shown in Figure 70 (*d*), so as to fill in the burbling space, the streamlines can then flow smoothly over the surface and resistance is made much less than otherwise for the same rate of airflow.

Fig. 71.

Streamlined object

An object of this shape, round in front and pointed behind, is said to be *streamlined.*

Note how the fish shown in Figure 71 is streamlined. Many fishes are thus obviously streamlined, doubtless as the result of natural selection: a fish that was more effectively streamlined than another could better gather its food and escape its enemies; hence that fish — and its type — survived, while the clumsier fish disappeared.

Airplane designers make fuselages of this general streamlined shape to hold down the air friction; and most struts and wires on airplanes are streamlined in cross section, instead of being cylindrical. In fact, the airplane designer attempts to streamline or *fair* all structures — such as radio antenna struts, landing gear, and engine radiators — that would otherwise produce a bad drag, or slowing up of the plane in flight.

The wings as airfoils

The wings of an airplane may be considered as the most representative airfoils. Their function is to produce lift. Wings are designed, therefore, to produce as much lift as possible in proportion to their drag, or, as we might say, to produce as little drag as possible in proportion to their lift.

In order that a wing capable of producing a given amount of lift will have as little drag as possible, it is given a streamlined cross section. The lift is then obtained, as explained below, either by curvature (camber) of the wing section or by setting the wing at an angle to the direction of its motion through the air, or both.[1]

[1] Some writers prefer to use the term "streamlined" to refer to objects shaped so that the air resistance is reduced to a minimum. According to that usage a wing that has camber (as explained below) or otherwise produces lift is not considered as entirely streamlined.

Direction of an airfoil section

Figure 72 shows the cross section of each of various types of wings. In discussing the attitude of an airfoil section with reference to the direction of flow of air, it is necessary to designate its direction (the way it is pointing). In the case of a double convex airfoil, as at (*a*), its direction is defined as that of a line from the foremost point of the *leading edge* (front) to the hindmost point of the *trailing edge* (rear), as shown by the dotted line.

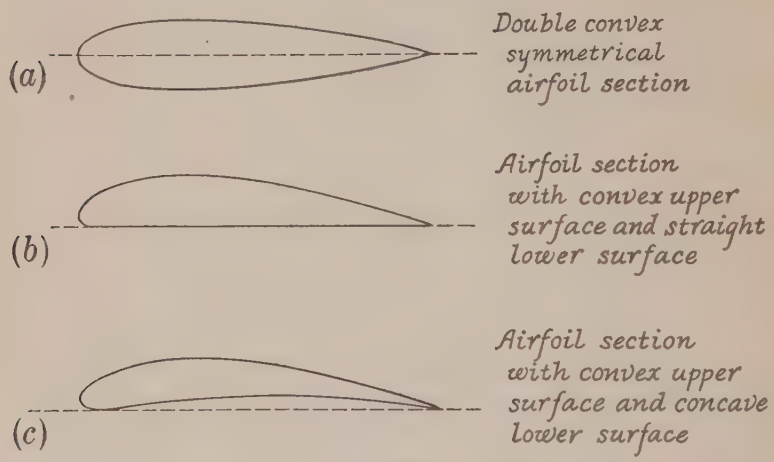


FIG. 72.

In the airfoil sections at (*b*) and (*c*), the direction of the section is considered to be represented by the dotted lines (a line coinciding with the straight edge, or tangent to the lower edge of the section at two points).

Chord of an airfoil section

Besides knowing the direction of an airfoil section, we need to have a measure of its length. For this purpose it is customary to use the *projection* of the airfoil on the direction line. The *projection* of an object on a line is like the shadow

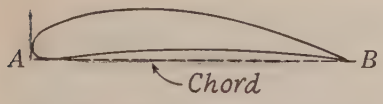


FIG. 73. The chord of an airfoil.

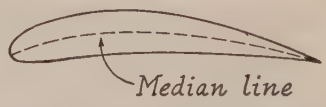


FIG. 74. Camber in an airfoil.

of the object on the line made when the sun shines perpendicular to the line. In Figure 73 the line AB is the *chord* of the airfoil section. A is the foot of the perpendicular to the direction line from the foremost point of the leading edge. The chord of an airfoil is considered therefore as showing both its direction and length.

Camber of an airfoil

The term *camber* refers to the curvature of an airfoil or its surfaces. The *mean camber* of an airfoil may be considered as the curvature of the median line of the airfoil (dotted line in Figure 74). The airfoil section shown at (*a*) in Figure 72 has no mean camber; the section at (*b*) has camber in the upper surface but no camber in the lower surface and has slight mean camber; the section at (*c*) has considerable mean camber.

Angle of incidence

The angle that the chord of an airfoil makes with a line parallel to the longitudinal axis of a plane is called the *angle of incidence* of the airfoil, as shown in Figure 75.

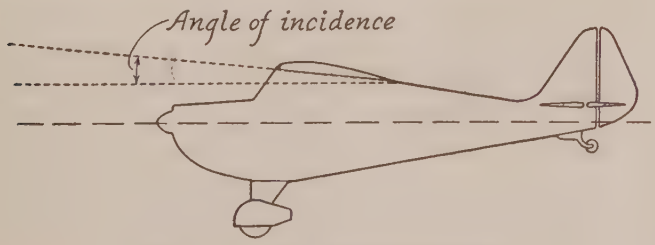
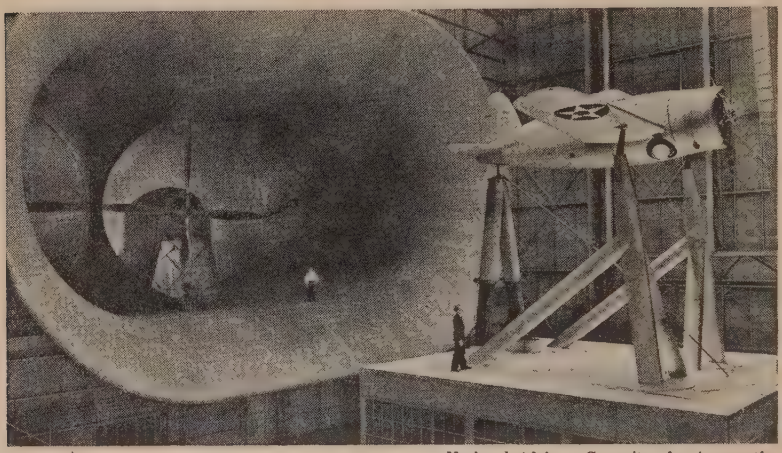


FIG. 75. The angle of incidence.



National Advisory Committee for Aeronautics

FIG. 76. An airplane being tested in the wind tunnel at Langley Field, Virginia. It is the largest wind tunnel in the world. Propellers operated by two 4000-horsepower motors produce a wind velocity of 118 miles per hour.

Relative wind

In studying airfoils, it makes no difference whether the plane or airfoil is flying through stationary air or the plane is stationary and the air flows past it. In fact, airplanes are tested in what is called a *wind tunnel*, the plane being stationary and a strong current of wind being forced past it.

What matters is the direction of the air *relative to the plane* or airfoil. When you understand this, you understand one kind of *relativity*.

The direction of the air with respect to the plane, or relative to the plane, is called the *direction of relative wind*. If a plane is flying horizontally, the relative wind is horizontal. If the plane is descending, the relative wind is slightly upward, and if the plane is climbing, the relative wind is slightly downward, as shown in Figure 77. Obviously the direction of relative wind is always exactly opposite the motion of the plane with reference to the air.

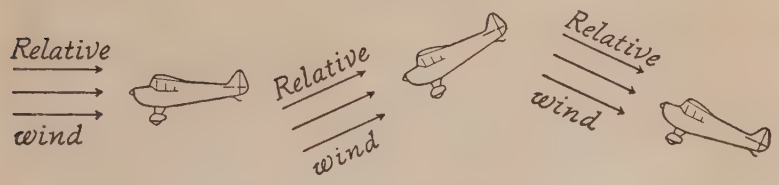


FIG. 77. Direction of relative wind.

Angle of attack

The angle between the chord of an airfoil section and the direction of relative wind is called the *angle of attack* of the airfoil, as shown in Figure 78. The angle of attack of an airfoil section is independent of its shape and of its position relative to the fuselage. It is wholly a matter of the direction of the airfoil section with reference to the direction of motion of the air toward the section.

The angle of attack of a wing can be different, of course, from the angle of incidence, as in Figure 55, page 80. In ordinary level flight the angle of attack is about equal to the angle of incidence.

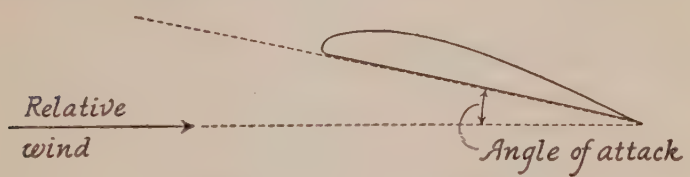


FIG. 78. The angle of attack.

Air pressure

It has been said that we live at the bottom of an ocean of air. It is true. Air has weight the same as water. A cubic foot of air at sea-level density weighs about .077 of a pound. Hence the air in a room 10 feet square and 10 feet high weighs about 77 pounds.

A column of air one square inch in cross section extending as high as the air reaches weighs about 15 pounds; hence the

air presses on all objects with a force of about 15 pounds to the square inch. At a given altitude it presses equally in all directions; it presses equally on the top and the bottom of the wings of a stationary airplane.

Lift

When an airfoil of the shape shown in Figure 79 is pulled rapidly through the air at a slight angle of attack as shown,

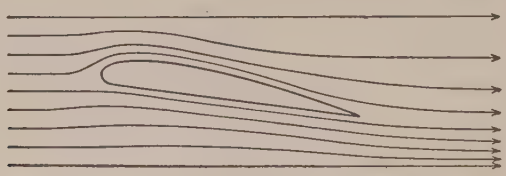


FIG. 79. An airfoil at slight positive angle of attack.

the air pressure on the underside of the airfoil is greater than atmospheric pressure (the pressure of the undisturbed air in advance of the airfoil) and the air pressure on the upperside of the airfoil is less than atmospheric pressure, and this difference in pressure produces *lift*. In common airfoils the reduction in pressure above the wing may be twice as great as the increase in pressure below the wing. Some persons like to speak of this as one-third lift from below and two-thirds suction from above, but actually we know that all the lift comes from below the wing. (Air particles can push but they cannot pull.) The lift is caused by that pressure under the wing which is in excess of that above the wing.

BERNOULLI'S LAW

Lift at zero angle of attack

It has been found possible to get lift from an airfoil even when presented to the air at a zero angle of attack, as shown in Figure 80. This is possible because the curvature of the

upper surface of the wing produces a diminution of pressure on this surface, and even though the pressure on the lower surface is not increased at all there is greater pressure on the lower surface than on the upper surface. This difference in pressure creates lift. In order to understand the reason for the reduced pressure on the upper surface, it is necessary to understand Bernoulli's law regarding the conservation of energy.

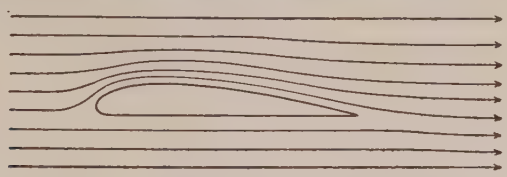


FIG. 80. An airfoil at zero angle of attack.

Kinetic and potential energy

A body in motion has ability to do work. Ability to do work is called *energy*. The power to do work that a body has because of momentum (weight and motion) is called *kinetic energy*.

A body in a high position (such as the hoisted hammer of a pile driver) has the ability to do work because of its position. It is not in motion, but gravity will put it in motion if it is let go. Ability to do work which a body has because of its position is called *potential energy*. ("Potential" means possible; so potential energy is possible energy.)

Conversion of energy

If you throw a tennis ball into the air, it has potential energy at the top of its path. As it descends, its height is reduced and its speed is increased. Its potential energy is being *converted* into kinetic energy. When the ball reaches the ground we may say that all its potential energy has been converted into kinetic energy. No energy is lost; it is merely converted from one form to another.

American Airlines

FIG. 81. A Douglas transport plane over Niagara Falls.

Pressure energy

When the ball strikes the ground its velocity is suddenly reduced to zero. But the ball is compressed and has the power to expand again and bounce into the air.

The kinetic energy that the ball had while descending was converted into a third kind called *pressure energy*. Some of the kinetic energy was converted also into *heat energy* which was scattered and wasted, but no energy was destroyed.

Conservation of energy

When energy is converted from one kind into another, no energy is actually destroyed. We may lose track of it, but it exists in some form. The statement of this fact is called the *law of the conservation of energy*.

Bernoulli's law

Daniel Bernoulli, a Swiss mathematician born in 1700, has given a mathematical equation known as *Bernoulli's law* which expresses the fact that in a streamline flow of a fluid the sum of the kinetic energy, pressure energy, and potential energy of a given body of air is constant. By "fluid" is meant either a liquid or a gas. Air is a gas.

In dealing with airfoils we are not concerned with potential energy (the energy of height) because differences in height

are negligible. Bernoulli's law, as it applies to airfoils, comes down to this: *In a streamline flow, the greater the speed of the air the less the pressure of the air, and the less the speed of the air the greater the pressure.*[1]

Venturi tube

The operation of Bernoulli's law is most commonly illustrated with the *Venturi tube*, a tube with a narrowed *throat* as shown in cross section in Figure 82. If any fluid such as water or air is flowing through the tube, it flows more rapidly through the throat than through the rest of the tube.

If the diameter of the tube at *A* is one inch and that of the

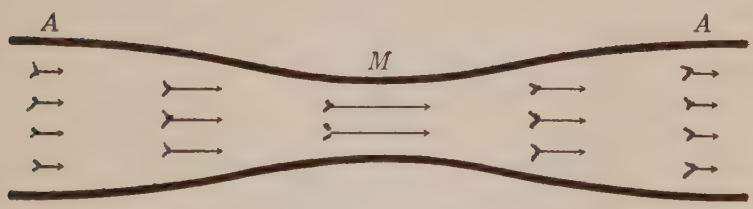


FIG. 82. A Venturi tube.

[1] One mathematical form of Bernoulli's law of the conservation of energy in a moving mass of fluid is as follows:

$$\text{Bernoulli's law: } \frac{v^2}{2g} + \frac{p}{w} + z = \text{a constant}$$

In this equation,

v = the velocity of the fluid in feet per second,
g = the acceleration due to gravity in feet per second, per second (g = about 32.2),
p = the pressure of the fluid in pounds per square foot,
w = the specific weight of the fluid in pounds per cubic foot,
z = the height in feet of the fluid above some reference line at which the potential energy would be considered as zero,
$\frac{v^2}{2g}$ = the kinetic energy of one pound of the fluid,
$\frac{p}{w}$ = the pressure energy of one pound of the fluid, and
z = the potential energy of one pound of the fluid.

The law leaves out of account the fact that a fluid is slightly compressible and also disregards any conversion of kinetic energy into heat energy.

throat at M is half an inch, the cross section of the throat at M is only one fourth as large in area as the cross section of the tube at A. Hence the fluid flows four times as rapidly at M as at A — if air were flowing at A at 30 miles an hour, it would be flowing at M at 4×30 or 120 miles an hour — an *increase* of 90 miles an hour.

Experiments demonstrating Bernoulli's law

You can demonstrate Bernoulli's law yourself by the experiments that follow.

Experiment 1. Hang a small ball (preferably a ping-pong ball) by a string and blow a stream of air past it from a straw, as shown in Figure 83 (*a*). Note how the ball is pushed over toward the fast-moving air from the straw which presses on it less than the stationary air on the other side.

Experiment 2. Push a pin through the center of a card up to the pinhead, and place the card against a spool with the pin lying in the hole of the spool, as shown in the inset in Figure 83 (*b*). Begin blowing gradually, then blow very hard through the spool. You can do so without blowing the card away from the spool. The air flowing outward on the side of the card nearest the spool presses less on the card than the air on the other side and the card is actually pressed up close to the spool while you are blowing hardest. This will happen even when pointing the spool downward.

Experiment 3. Whittle a cork down to a sphere and smooth the surface with sandpaper. Hold the cork ball a few inches above the end of a drinking straw pointing upward, as shown in Figure 83 (*c*). Blow gently through the straw and let go of the ball. With a little practice you can balance the ball, so to speak, in the air a few inches above the end of the straw as long as your breath lasts. (If you have difficulty in balancing the ball, put a small pin through it and begin with the pin projecting into the end of the straw.)

Let us say the ball falls off the jet to the position shown in the inset circle. When the ball is in this position, the air away from the jet is flowing past the ball slowly or not at all, and the air on the jet side is flowing past it rapidly and therefore exerting less

sideward pressure. The air away from the jet side, therefore, pushes the ball over into the jet and up it goes again. So it bounces up and down on top of the jet. Try balancing the ball on the jet of air escaping from a home steam radiator valve.

Experiment 4. Bend a strip of cardboard to the shape of the upper surface of a wing section, as shown in Figure 83 (*d*). Hang the strip of cardboard over a pencil as shown. Blow down past the convex side of the strip, as shown in the inset. Note how the strip moves toward the stream of air. The strip can be lifted in this way even up to a level position, as shown in the figure, merely by blowing air over the top of the strip.

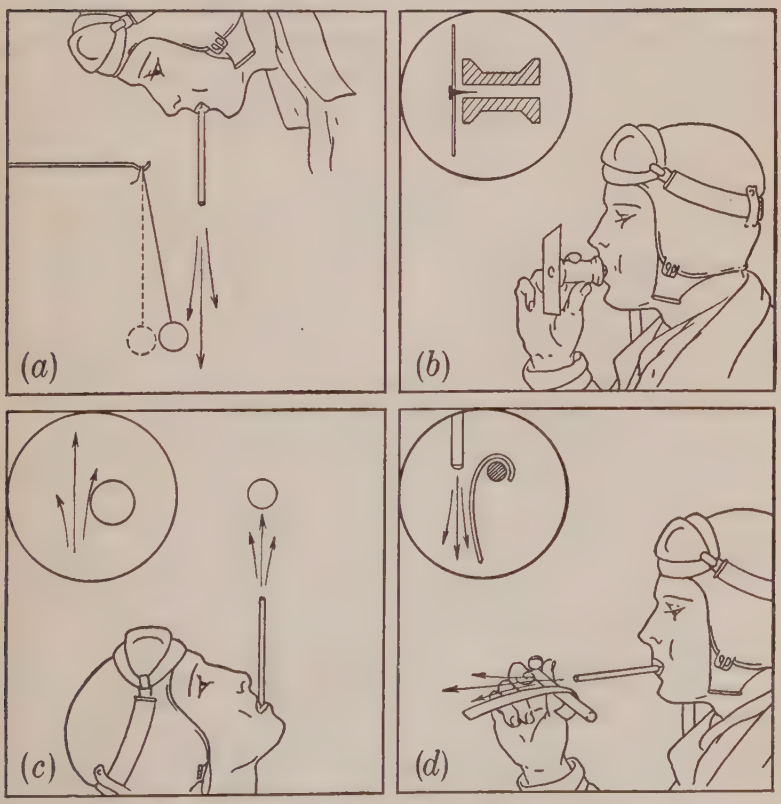


Fig. 83. Experiments illustrating Bernoulli's law.

Lift with increased speed of air

Returning to the wing of the airplane, the theory of lift is as follows: Because of the camber (curvature) the air has to flow farther to go over the top of the wing than to go under it; but the air that flows over the wing must do so in the same time that is taken by the air that flows under the wing. Hence the air flowing over the wing must go faster than the air flowing under the wing, and the faster-flowing air over the wing presses less on the wing than the slower-moving air under the wing; hence the lift.[1]

In the case of a symmetrical airfoil, as shown at the top in Figure 72, the curvature causes an equal reduction of pressure both above and below when at zero angle of attack. Hence a symmetrical airfoil at zero angle of attack has no lift.

EFFECT OF CENTRIFUGAL FORCE

Distribution of pressure on the upper surface of an airfoil

Bernoulli's law by itself does not explain the distribution of pressure over the upper surface of the airfoil. To understand this we must investigate the influence of momentum of the air as it flows in various curved paths near the airfoil.

Newton's first law of motion states that a body at rest tends to remain at rest and a body in motion tends to remain in motion in a straight line at the same speed. The stationary body will remain stationary unless acted upon by some force; and a body in motion will remain in motion in a straight line at the same speed unless acted upon by some force.

[1] We should not consider that the increased speed of the air over the wing *causes* the decrease in pressure of the air. It might be more precise, perhaps, to say that the greater distance over the airfoil gives the air greater space in which to move and hence affords the opportunity for some of the pressure energy to be expended in speeding up the air to occupy the greater space. In other words, the greater distance over the top of the wing caused both the greater speed of airflow and the accompanying lesser pressure.

Inertia

The force with which a stationary body offers resistance to being moved and the force with which a moving body resists having its motion stopped or changed in direction is called the *force of inertia.*

Newton's second law of motion states that a force is required to overcome the inertia of a stationary body and give it motion, and a force is required to overcome the inertia of a moving body by either stopping its motion or changing the direction of its motion. Newton's second law states that the force required to produce a change in the velocity of a body is in proportion to the mass of the body and is also in proportion to the rate of change in the velocity of the body produced by the force (either changing the amount or the direction of the motion).

The inertia of a moving body (its tendency to resist change of its motion) is often called *momentum.* When we speak of the inertia of a body we usually have reference to the inertia of a stationary body.

Centrifugal force

When a body is forced to move in a circular path it offers resistance in the direction away from the center of the curved path. This resistance is called *centrifugal force.* Centrifugal force is discussed more fully in the next chapter in connection with banking a plane.

While particles of air are moving in the curved path *AB* in Figure 84, the centrifugal force tends to throw them in the direction of the arrows between *A* and *B* and hence causes the air to exert more than normal pressure on the front edge of the airfoil. But after the air particles pass *B* (the point of reversal of the curvature of the path) the centrifugal force tends to throw them in the direction of the arrows between *B* and *C* (causing reduced pressure on the airfoil). This

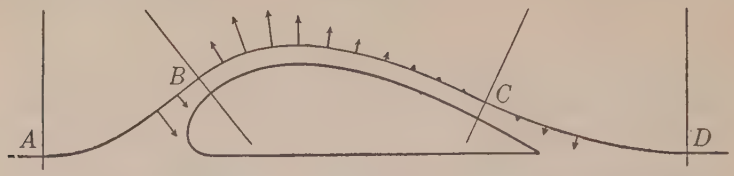


FIG. 84. Change of pressure produced by change of centrifugal force.

effect is held until the particles reach *C*, the second point of reversal of curvature of airflow. Again the centrifugal force is reversed and the particles may even tend to give slightly more than normal pressure on the trailing edge of the airfoil, as indicated by the short arrows between *C* and *D*.

Therefore, the air pressure on the upper surface of the airfoil is distributed so that the pressure is much greater than atmospheric pressure on the leading edge, causing strong resistance to forward motion; but the air pressure is less than atmospheric over a large portion of the top surface (*B* to *C* in Figure 84).

We assume that in the case of an airfoil at zero angle of attack the pressure on the lower surface of the airfoil is approximately that of the undisturbed air; and since the pressure on the upper surface in a downward direction is appreciably less than the pressure of the undisturbed air, we have an excess of pressure on the under surface which constitutes the lift.

Induced lift

This lift which comes from the reduced pressure of the air above an airfoil is called *induced lift.*

TOTAL LIFT

Dynamic lift

We have seen how, when an airfoil is presented to the wind at a positive angle of attack, the impact of the air on the under

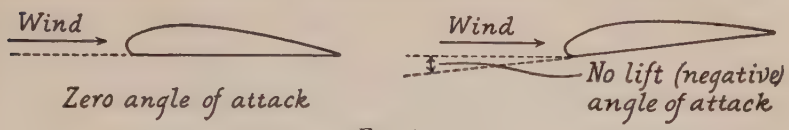


FIG. 85.

surface of the airfoil produces lift. This kind of lift is called *dynamic lift.*

The total lift is the sum of these values, which is merely the difference between the increased pressure below and the diminished pressure above the airfoil.

No-lift angle of attack

If we can get some lift even with "zero angle of attack" (zero angle between the arbitrary line called the chord and the direction of relative wind), there must be a negative angle of attack at which there is no lift. This angle is called the *no-lift angle of attack.* (See Fig. 85.)

Absolute angle of attack

The amount of upward turn an airfoil has made from its position of no lift is called the *absolute angle of attack.* We can think of this as being the angle from the position of "absolutely no lift."

Burbling

As in the case of the sphere, when an airfoil is presented to the air at a sufficiently great angle of attack — so that the centrifugal force of the air in rounding the leading edge is too great to permit the air to reverse its motion enough to flow downward smoothly over the upper surface — there is a tendency for "dead air" to collect in a space like that marked *S* in Figure 86, and the airfoil and dead air combined form a streamlined object of less

FIG. 86.

angle of attack. This tendency causes air to creep up the back of the airfoil from behind and to remain relatively motionless on the upper surface, thus (in region *A* in Figure 87) completely "spoiling" the streamline flow and lift. (Remember that according to Bernoulli's law air that has lost its speed has gained pressure thereby.)

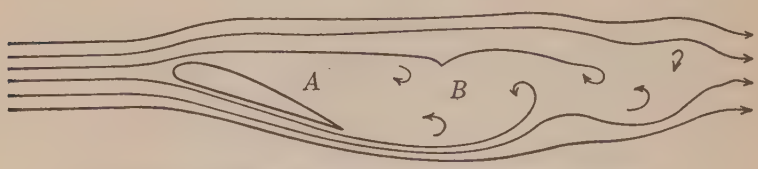


FIG. 87. Burbling produced by high angle of attack.

There is obviously a vigorous surging and burbling of air in the region marked *B* in Figure 87, where the streamlines of air are rushing past the so-called dead air. The term *burbling* is customarily used to describe this action.

Stalling

If a plane decreases its speed, the wings must have a higher angle of attack in order to get the same lift. If the plane continues to decrease its speed and increase the angle of attack of the wings, sooner or later that angle of attack is reached in which burbling begins.

When burbling begins and the wings lose lift on account of the burbling, the plane begins to sink slightly. This increases the angle of attack; this causes more burbling; this causes the wings to lose more lift; this causes the plane to sink more rapidly, etc. That is, the action of losing lift is *self-generating*.

Therefore, when burbling once starts as a result of too little speed for the angle of attack, the plane quickly *stalls*.

The term *flying speed* usually refers to the minimum speed at which the causes leading to burbling are not present.

Stalling at high speed

In the above discussion of stalling we have had in mind straight and level flight. As you will see in a later chapter, a great deal more lift is necessary to carry a plane around a sharp turn than to carry it in straight and level flight, especially at high speed. This is true whether the sharp turn is a level turn or an attempt to recover from a dive.

Therefore, if a pilot tries to make a sharp turn or to recover from a dive or loop at too high an angle of attack, the loss of lift due to burbling is such as to render the lift insufficient for its requirements and the centrifugal force causes the plane to "squash" or "mush" as in a pancake landing even at high speed. The plane is really stalling at high speed.

Every pilot should remember, therefore, that it is dangerous to try to make a very sharp turn or to dive close to the ground even at high speed. The pilot may think he has plenty of room above ground to recover from a dive — and perhaps would have if the plane did not squash — but in not allowing for this possibility he may find it impossible to pull the plane out of the dive in time and the plane will squash right into the ground in spite of the nose being high. Such an accident at high speed is very serious.

Lift sustains weight

Let us say an airplane has a wing area of 167 square feet or about 24,000 square inches. Let us assume that the plane with full load weighs 1200 pounds. This means that each square inch of surface under the wing needs to lift only $\frac{1200}{24000}$ or about $\frac{1}{20}$ of a pound in order that the total lift will sustain the fully loaded plane. One twentieth of a pound is only $\frac{1}{300}$ of 15 pounds; hence we need to induce a difference in pressure between lower and upper surfaces of the wings of only about $\frac{1}{300}$ of atmospheric pressure in order to get sufficient lift to sustain the plane.

Center of pressure

The combined effect of the pressure of the air on all points on the surface of an airfoil section may be thought of as a single force acting at a single point within the airfoil section. (Indeed, it is theoretically possible to substitute a single force of the proper magnitude and direction to take the place of the combination of all the actual forces acting on the airfoil, and having exactly the same effect.) This single force which equals the combined action of all the actual forces is called the *resultant reaction*.[1] At present we are dealing with the resultant aerodynamic reaction of an airfoil section only. The point in the airfoil section at which this single force must act in order to replace all the actual pressures is called the *center of pressure* (C.P.) of the section. (See Fig. 88.) The direction of the resultant force is represented by the arrow in Figure 88.

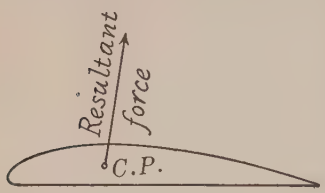


FIG. 88.

Center of pressure travel

The center of pressure in most airfoils has a tendency to change its position with change of angle of attack, presumably because of changes in the position of greatest centrifugal force. The center of pressure tends to move forward with an increase in angle of attack and backward with a decrease in angle of attack. This means that when the angle of attack of an airfoil is increased by tilting the wings (leading edge upward), the center of pressure (lift), moving forward, tends to tilt the wing still farther. This tendency gives wings an inherent quality of instability.

[1] This resultant pressure is called a reaction because it is merely the resistance of the wings to motion through the air. If you tie a rope to a tree and pull on the rope, the tree also pulls on the rope. The tree's pull is the *reaction* to your pull and is always exactly equal to it. Similarly, the pressure of air on the wings is a reaction to the forces of gravity and propeller pull.

If an airfoil had no air friction, the pressure of the air would always be perpendicular to the surface; but air has slight viscosity and tends to adhere to the airfoil at its surface. Hence the pressure is not quite perpendicular to the surface. Moreover, the pressure on the front edge of the airfoil, tending to push the airfoil back, is much greater than the pressure on rear portions, tending to push the airfoil forward. These facts combine to cause the resultant aerodynamic force (total of all forces acting on the airfoil) to be not perpendicular to the chord but slightly to rearward of perpendicular, as shown in Figure 88. Actually the drag of a wing may be as little as $\frac{1}{20}$ of the lift, in which case the resultant would act less than 3° to the rear of perpendicular to the chord.

Questions

1. What is an airfoil?
2. What is burbling?
3. What shape is a streamlined object?
4. What is meant by an airfoil section?
5. What is the chord of an airfoil that has a flat under surface?
6. What is meant by camber?
7. What is the angle of incidence of a wing?
8. What is the direction of the relative wind?
9. What is the angle of attack of a wing? (Compare angle of attack and angle of incidence.)
10. About how much does the air in a room 20 feet square and 10 feet high weigh?
11. What is the pressure of the atmosphere in pounds per square inch?
12. What produces lift in the case of an airplane at positive angle of attack?
13. Can an airfoil have lift at zero angle of attack?
14. What is kinetic energy?
15. What is potential energy?
16. Illustrate how potential energy is converted into kinetic energy.

17. Illustrate how kinetic energy is converted into potential energy.
18. What is the law of the conservation of energy?
19. Complete this sentence: Bernoulli's law states that the sum of . . .
20. Does Bernoulli's law pertain to liquids only? to gases only? to all fluids?
21. What is a Venturi tube?
22. If the throat of a Venturi tube of circular cross section is one third as wide as the main tube, the speed of a fluid through the throat is how many times as great as the speed of the fluid through the main tube?
23. If a jet of air is blown past a ping-pong ball hanging by a string, will the ball remain stationary, or move toward the jet of air, or move away from the jet?
24. If a Venturi tube is placed in the air stream on the side of an airplane and a second tube is attached perpendicularly to the throat of the Venturi tube and the other end of the tube is open, will the air in the second tube tend to flow into the Venturi tube or away from it?
25. Can you explain why a ping-pong ball will remain suspended in a vertical jet of air?
26. Can a symmetrical airfoil have lift at zero angle of attack?
27. What characteristic of an airfoil determines how the pressure will be distributed over its surface?
28. What is Newton's first law of motion?
29. What is Newton's second law of motion?
30. What is the force of inertia?
31. What is the force of momentum?
32. What is centrifugal force?
33. Explain the reason for pressure that is greater than atmospheric pressure on the front edge of an airfoil.
34. How does centrifugal force account for the fact that the position of least pressure is on top of the wing near the front?
35. What is induced lift?
36. What is dynamic lift?
37. What is meant by the no-lift angle of attack?

38. What is the absolute angle of attack?
39. What causes burbling in the case of an airfoil?
40. Explain the cause of a plane's stalling rather suddenly.
41. What is meant by a stall being self-generating?
42. In a light plane, by about what per cent of the total pressure on the underside of the wing must the pressure on the upperside be reduced in order to get enough lift to support the plane?
43. What is meant by center of pressure of an airfoil section?
44. What is meant by the resultant reaction of an airfoil?
45. Explain how the movement of the center of pressure can cause instability in a wing.
46. What effect does viscosity of the air have on the direction of pressure on a moving airfoil?
47. What factors combine to give the resultant aerodynamic force on an airfoil a direction not perpendicular to the chord but slightly rearward?

Pan-American Airways

FIG. 89. Atlantic Clipper taking off from marine base, La Guardia Field, New York, for a regularly scheduled flight to Europe. This is a "water plane" or flying boat. Most flying boats, like this one, are high-winged to keep the wing and engines high above waves and spray. What appear to be small low wings are hydrostabilizers which give the boat static lateral stability when resting on the water. They also serve as fuel tanks, serve as a platform over which the passengers board the plane, and supply some lift in flight.

12

FORCES ACTING ON A PLANE

YOU cannot really understand the flight of a plane unless you know the laws governing the forces acting on a plane. And if you do know those laws, it is possible for you to understand and explain the motion of a plane under all ordinary conditions of flying or gliding.

You have already learned Newton's first law of motion. We may state this fundamental law of physics in a different way and say that a body which is in equilibrium is either at rest or moving at a uniform rate in a straight line; and, conversely, that a body which is at rest or moving at a uniform rate in a straight line is in equilibrium.

A body in equilibrium

A body is in equilibrium when every force acting on it is opposed by an equal and opposite force. Thus, if a plane is resting on the ground, the force of gravity tries to pull it toward the center of the earth; but the surface of the ground resists this pull with an equal force upward.

Vectors

We may represent the amount and direction of a force by an arrow or a line. The length of the arrow shows the amount of the force (each inch of line might represent 100 pounds of force); and the direction of the arrow shows the direction of the force. Such an arrow is called a *vector*.

We may represent the forces acting on a plane resting on the ground by two vectors. The vector *OG* in Figure 90 (*a*) would represent the force of gravity on the plane, and the

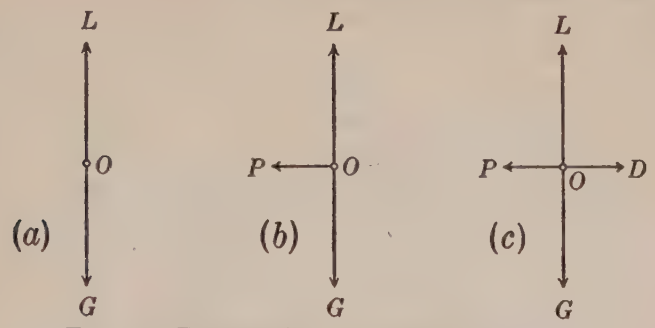


FIG. 90. Forces acting on a plane on the ground.

vector OL would represent the upward force of the ground on the plane (which is thought of as being at O). Since the two forces are equal and opposite, the plane is in equilibrium. Or we may say that since the plane is at rest and therefore in equilibrium, we know that the two forces are equal and opposite.

In drawing vectors we represent the forces as if they acted on the center of gravity of the body. The *center of gravity* of a plane is a point within the plane, such that if the plane were suspended at that point it would have no tendency to turn in any direction. Point O in Figure 90 (a) represents the center of gravity of the plane.

Unbalanced force causes acceleration

There is another fundamental law of physics to the effect that any body which is acted upon by an unbalanced force will gain speed in the direction of the force.[1] The simplest example of the action of this law is a falling body. A falling body is acted upon by gravity and air friction only, but when starting from rest, the force of gravity greatly exceeds the air friction and a large part of the force of gravity therefore

[1] The change in velocity such as the change in number of feet per second, every second, is proportional to the force. For a given force the change in velocity is inversely proportional to the mass of the body — the greater the mass the less the change in velocity. This is another way of stating Newton's second law of motion.

is unbalanced. The unbalanced force of gravity causes the body to *accelerate* in motion (gain more and more speed). The greater the unbalanced force, the greater the acceleration (the greater the gain in speed).

Another example of an unbalanced force is seen in a plane on the ground starting to taxi. In addition to the forces *OG* and *OL* of Figure 90 (*a*) there is also the pull of the propeller, which we may represent by the vector *OP* in Figure 90 (*b*). The pull of the propeller is called *thrust*.

If the force *OP* is unbalanced, the plane starts to move and gains more and more speed along the ground.

However, very soon the friction of the wheels on the ground and the friction of the air against the plane act as a drag on the plane, opposing the pull of the propeller. If the engine is not turning the propeller very fast, the "drag" — that is, the resistance to forward motion — (represented by the vector *OD* in Figure 90 (*c*)) may come to equal the propeller pull, and the forces are then in equilibrium again, there being now four forces — *OG* and *OL* equal and opposite to each other, and *OP* and *OD* equal and opposite, as shown in Figure 90 (*c*). When this condition is reached, the plane ceases to gain in speed and moves forward at a uniform rate.

Forces acting on a plane in flight

Let us see now what forces are acting on a plane when it is in straight and level flight at a uniform rate. Since a plane in flight is sustained by the air and not by the ground as in the case mentioned above, it is necessary to understand how the lift furnished by the wings takes the place of the sustaining force of the ground in our system of balance of forces.

Resultant aerodynamic force

So far we have considered only the combined force (reaction) of air around an airfoil section. If we thought of the wings

as cut perpendicular to the span into slices one inch wide, each slice would have its own resultant force. The sum of these forces for all slices of the wings would be the lift of the wings as a whole.

We know, however, that all other parts of the airplane and especially the fuselage are also acted upon by air forces; hence we need to consider a single force which may be thought of as having the combined effect of all aerodynamic forces on the airplane. Let us call this the total *resultant aerodynamic force* on the airplane. It is this force that affords the lift of the air on the airplane.

It is possible to fly a properly balanced plane in straight and level flight without touching the wheel or stick or even the rudder pedals. When an airplane is flying level in a straight line with hands off, we may think of the resultant aerodynamic force on the airplane as acting at the center of gravity.

Forces acting on the plane

We may now represent four forces acting on a plane.

We may represent each force by a vector. As explained previously, the beginning point of a vector shows the point of application of the force which it represents; the direction of the vector represents the direction of the force; and the length of the vector measured to some given scale of units represents the amount of the force. In Figure 92, point O is the center of gravity; vector OG represents the force of gravity

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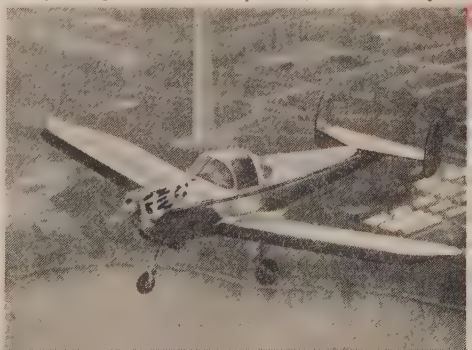


FIG. 91. The Ercoupe, a light plane of unusual type. It has the tricycle landing gear. The rudders, ailerons, and nose wheel are interconnected and are operated by a wheel. The plane is flown in much the same way as an automobile is driven.

on a flying plane; vector OP represents the pull or *thrust* of the propeller; vector OW represents the resultant aerodynamic force on the wing, but we may think of it now as the pull of the wings on the plane (wing pull). Vector OD_p represents the force of the air against the airplane, exclusive of the wings, resisting its forward motion.

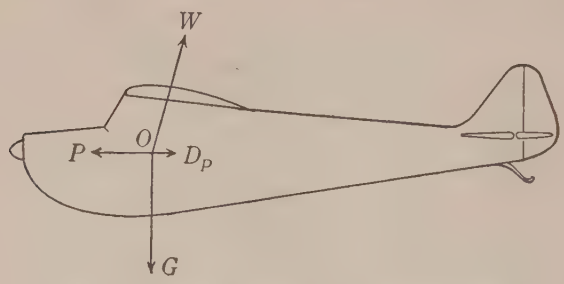


FIG. 92. Forces acting on a plane in flight.

Parasite drag

All force resisting forward motion is called *drag*, and the portion of such force on the airplane other than on the wings is called *parasite drag* (D_p).

Now it is sometimes not convenient to deal as a unit with a slanting force such as the wing pull OW, and for convenience we divide the force OW into two parts. In order to understand how to do this, we need to understand the *parallelogram law of forces.* This law is well worth understanding for its application to forces other than those acting on an airplane.

Parallelogram law of forces

The law of physics known as the parallelogram law of forces is that if any three forces OA, OB, and OC are so related that vectors OB and OC are two sides of a parallelogram and vector OA is the diagonal of the parallelogram,

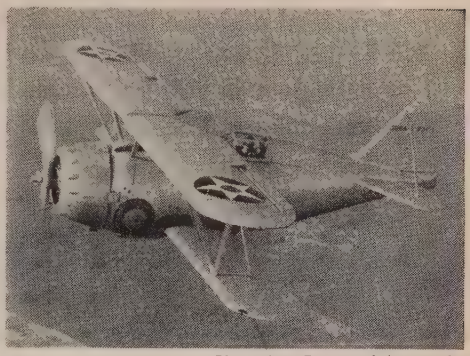


FIG. 93. A Grumman fighter plane used on aircraft carriers. This is a biplane, as it has two wings; the lower wing is somewhat behind the upper wing, and therefore we say that the plane has positive stagger. The wing is straight across — the plane has no sweepback; and since the wing is of the same width throughout, except for the tips, we say it has no taper. The landing gear is withdrawn into the fuselage — is retractable.

U. S. Navy Bureau of Aeronautics

as in Figure 94, then the force OA is the equivalent of the two forces OB and OC acting together. We say that OA is the *resultant* of the two forces OB and OC. Or we say that the force OA may be *resolved* into two *component* forces, OB and OC.

In any system of forces the components of a force may theoretically be substituted for the force, or any resultant force may be substituted for the forces of which it is the

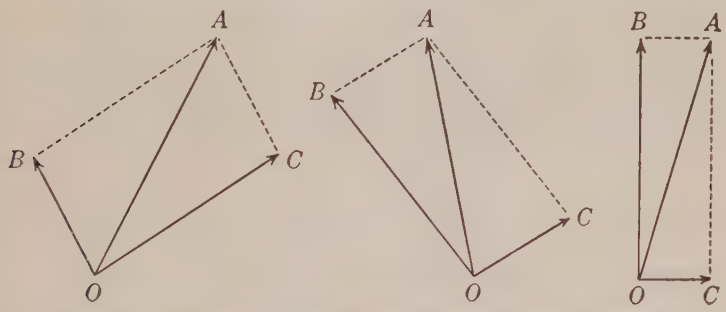


FIG. 94. Illustrating the parallelogram law of forces.

resultant, and no change will take place in the system of forces. (If the system was in equilibrium before the substitution, it will be in equilibrium also after the substitution.)

If we have a force represented by a vector OW as in Figure 95 (a) and wish to resolve it into two components, one

vertical and one horizontal, we let OW be the diagonal of a rectangle whose sides OL and OD are vertical and horizontal, as shown in Figure 95 (b). The lines OL and OD are the vertical and horizontal components of the force OW.

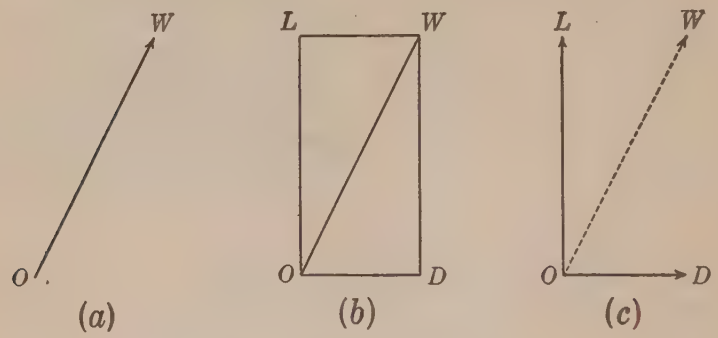


FIG. 95.

Now we may find the horizontal and vertical components of the slanting force OW in Figure 92 and substitute these for OW in the system of vectors shown in Figure 92. Figure 96 shows how this is done.

In Figure 96 (a) we see the force OW (which we have called *wing pull*) resolved into its vertical and horizontal components OL and OD_w. Vector OL shows the amount of lift (L) in the wing pull; it is the lift component of wing pull. Vector

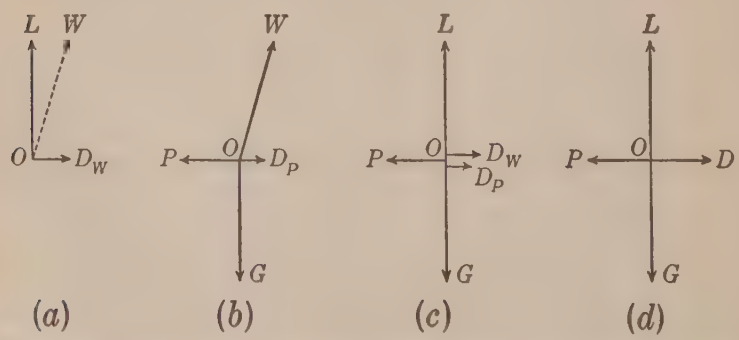


FIG. 96. Vertical and horizontal forces acting on a plane in flight.

OD_w shows the amount of drag (D_w) in the wing pull; it is the drag component of wing pull. In these figures the drag is represented as much greater in proportion to the lift than it actually is.

In Figure 96 (*b*) is reproduced the system of forces shown in Figure 92.

In Figure 96 (*c*) the wing pull OW has been removed and its components, OL and OD_w, substituted.

In Figure 96 (*d*) the two drag vectors, D_w and D_p (wing drag and parasite drag), have been added together to give one vector showing total drag (D) represented by vector OD.

This vector system, in Figure 96 (*d*), shows the forces acting on the plane to be in equilibrium — propeller pull or "thrust" (OP) balances total drag (OD), and lift (OL) balances the force of gravity (OG), the same as in Figure 90 (*c*).

A plane taking off

What happens to the forces acting on a plane as it takes off is that the component OL of wing pull (Fig. 92) gradually increases and the force of the ground pressing up on the wheels, represented by vector OL in Figure 90 (*c*), gradually decreases until finally the lift of the wings is sufficient to sustain all the weight, at which time the plane is able to leave the ground.

Forces acting on a climbing plane

Let us see what happens when the nose of a plane is tilted up; that is, when the plane is made to climb.

First, we must realize that the wings are tilted back, and hence the (resultant) wing pull OW is now as shown in Figure 97; that is, vector OW is tilted farther back.

We know that the force of gravity acting on the plane (its weight) is the same in climbing as in any other flight; that is, it remains constant both in amount and direction (down-

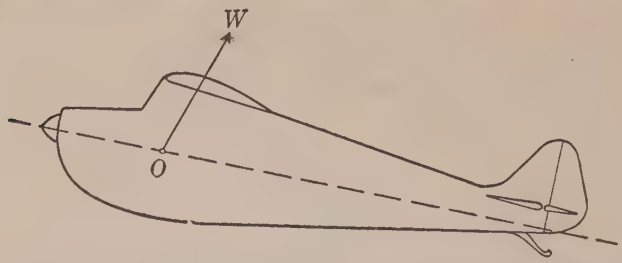


FIG. 97. Resultant reactions in level and climbing flight.

ward). We may represent the force of gravity by the same vector OG as in Figure 92. (See Fig. 98 (a).)

Now since the propeller pull (thrust) is slightly upward, we must represent this by a slanting vector, such as OP in Figure 98 (a). The parasite drag is parallel to the relative wind and therefore in the direction exactly opposite to OP; hence we will represent this by vector OD_p in Figure 98 (a).

We need to resolve wing pull OW of Figure 98 (a) into a vertical component and a drag component. The drag component must be parallel to OD_p in order that we may later combine the two drag vectors. This resolving is done, as shown in Figure 98 (b), by letting OW be the diagonal of a parallelogram whose sides are in the direction of the components we are seeking. Vector OS is the sustentation component and OD_w the drag component of the wing pull.

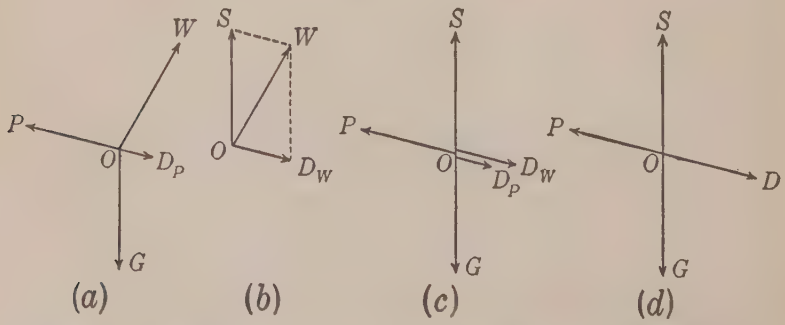


FIG. 98. Balance of forces acting on a plane in climbing flight.

We are substituting the word *sustentation* for *lift* in this case because the word "lift" has come to have the technical meaning of force perpendicular to the direction of relative wind. Hence we need a new word for the vertical component of wing pull when the relative wind is not horizontal, as in this case. *Sustentation*, therefore, always means vertical force upward.

Figure 98 (*c*) shows components OS and OD_w of Figure 98 (*b*) substituted for the wing pull OW; and in Figure 98 (*d*) the single drag vector OD represents the sum of wing drag vector OD_w and parasite drag vector OD_p. Again we see the forces in equilibrium.

Now the drag component OD_w of wing pull is greater in a climb than in level flight, as shown by comparing Figure 98 (*b*) with Figure 96 (*a*). And the parasite drag OD_p in Figure 98 (*a*) is the same as OD_p in Figure 96 (*b*). Therefore, the total drag OD in Figure 98 (*d*) is greater than the total drag OD in Figure 96 (*d*). This shows why it *takes more power to climb than to fly level at the same speed.*

Forces acting on a plane in a glide

In order to glide with power off (or virtually so, as when the engine is merely idling), a plane must have its nose down, as shown in Figure 99. In that case the reaction OW is

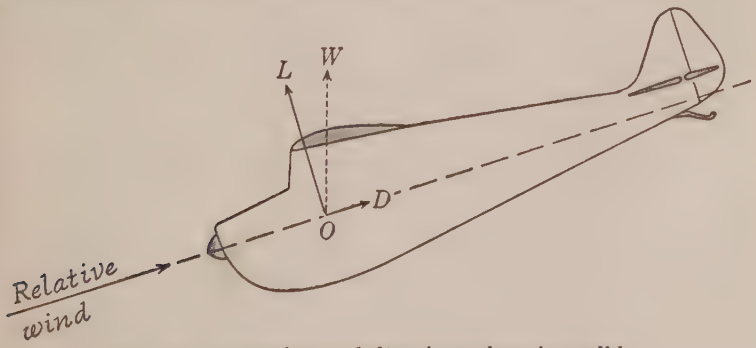


FIG. 99. Reaction and drag in a plane in a glide.

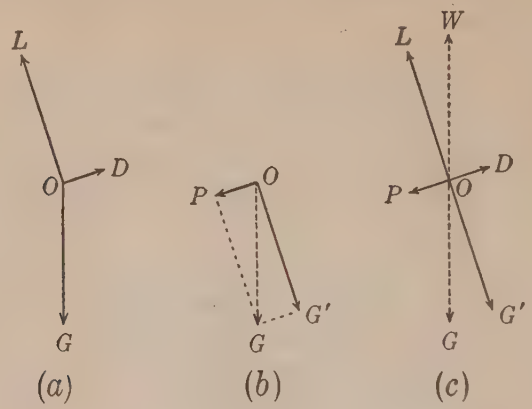


FIG. 100. Balance of forces on a plane in a glide.

vertical, the drag [1] is in the direction of the relative wind, and the "lift" is perpendicular to the relative wind, as shown by *OL*.

We know that gravity is the only force acting to produce propulsion (forward pull); hence the three forces, "lift" *OL*, drag *OD*, and gravity *OG*, must be balanced in a system, as shown in Figure 100 (*a*). To understand how the system can be in equilibrium with a force to overcome drag, we may think of the force of gravity as resolved into two components, as shown in Figure 100 (*b*), one in the direction *OP* (opposed to drag) and one in the direction *OG'* (opposed to the lift which the wings have in the position in which they are in the glide).

Component *OP* furnishes the propelling force to overcome drag and keep the plane moving forward.

If components *OP* and *OG'* are substituted for *OG* in Figure 100 (*a*), we have Figure 100 (*c*), in which the forces are directly opposed to one another.

We know that if the plane is gliding at a uniform rate the forces are in equilibrium and hence that the propelling force

[1] In this case, for simplicity we may think of the vector *OD* as containing the parasitic drag. *OW* therefore is the resultant of the lift and total drag.

OP equals the drag. (If the propelling force is greater than the drag, the plane will go faster and faster until the drag becomes equal to the propelling force.)

Also we know that the "lift" *OL* is just equal to the component *OG′* of gravity, because it is merely a reaction to that component.

Steep glide

If the plane is nosed down to glide more steeply, the direction of "lift" *OL* is farther forward, as shown in Figure 101 (*a*), and the direction of drag is steeper. When gravity is resolved into components in these directions, as shown in Figure 101 (*b*), we find a stronger propelling component *OP*. The amount by which this new propelling component exceeds the drag constitutes an unbalanced force which accelerates the motion of the plane (increases its forward speed) until the drag *OD* equals the increased propelling component *OP*. (Drag *OD* increases as the speed increases.) The new balance of forces is then as shown in Figure 101 (*c*).

Terminal velocity

If the plane is nosed far down to glide very steeply, the forward component *OP* of gravity may be so great that the speed of the plane will increase at a very rapid rate — attaining much more speed than is possible in level flight — before

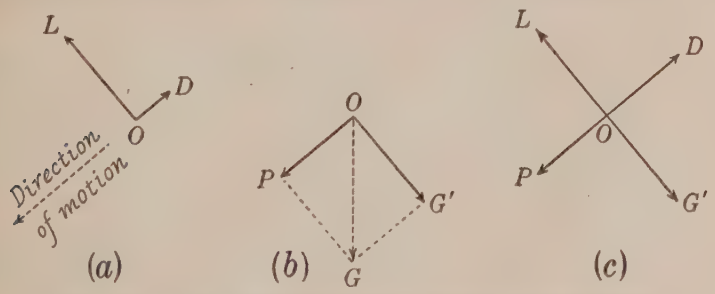


FIG. 101. Balance of forces on a plane in a steep glide.

the air resistance equals the forward pull. In a vertical dive this maximum speed is called the power-off *terminal velocity* of the airplane.

Cause of a spin

In Chapter 8 you learned the nature of a spin. It is thought that when a plane stalls, one wing sometimes stalls slightly sooner than the other, then that wing drops, tipping the plane to one side. Let us say it is the left wing that stalls first and drops. As the left wing drops, its angle of attack is increased and it stalls still more, whereas the right wing, being lifted slightly by the lowering of the left wing, has a decreased angle of attack and therefore tends less to stall.

A spin is a case of stalling in which one wing, say the left, is given a strong tendency to stall first. In that case the right wing, because of sufficient decrease in angle of attack, does not stall and so retains its lift.

The left wing, losing its lift, loses its forward component of gravity, but the right wing retains its forward component of gravity and this force rotates the plane counterclockwise. The forward motion of the right wing in the spin retains its lift and its forward component of gravity and the backward motion of the left wing prevents it from regaining lift or any forward component of gravity. The centrifugal force of the spinning tends to keep the wings level by forcing them as far away as possible from the axis of spin, and similarly to keep the tail from approaching the axis of spin.

All these tendencies hold the plane at a more or less fixed angle relative to the axis of rotation and prevent it from gaining speed beyond a certain amount either downward or in rotation. That is, when once fully spinning, the plane tends to continue spinning more or less uniformly.

Some planes tend to spin with the nose pointing down rather steeply; others tend to spin more nearly level. This latter type of spin is called a *flat spin.*

EXERCISE 1. What is the direction and amount of the resultant of two forces acting at point P — one a force of 150 pounds acting in the direction 45° (from north) and the other a force of 100 pounds acting in the direction 300°?

EXERCISE 2. If a plane weighs 1200 pounds, what is the component of the force of gravity that propels the plane in a glide without power if the gliding angle is 10°? 15°?

EXERCISE 3. What component of gravity remains to be balanced by lift in each case in Exercise 2?

QUESTIONS

1. A body that is in equilibrium is either at rest or moving — how?
2. When a body is in equilibrium every force acting on it is opposed by what?
3. What is a vector?
4. What is the center of gravity of a plane?
5. What happens to a body when an unbalanced force acts upon it? Can you give an example?
6. What is required to make a plane travel faster and faster along the ground?
7. What force is opposed to the weight of a plane as it rests on the ground?
8. What happens to the upward force of the ground against a plane as it gains speed?
9. What forces act on a plane when it is in straight and level flight?
10. Can you draw vector diagrams to show why it takes more power to climb than to fly level at the same speed?
11. What is meant by the force of sustentation as contrasted with lift?
12. What force acts to overcome drag and afford propulsion (push) in a plane gliding without power?
13. What prevents a plane that is flying vertically downward from increasing in velocity indefinitely?
14. What is meant by terminal velocity?

13

STABILITY IN A PLANE

IT IS possible to construct an airplane so that with the correct adjustment of speed and controls it will fly level in a straight line without the pilot touching the controls. This is possible because of devices which give a plane qualities that keep it stable.

Kinds of stability

There are various kinds of stability, all of which are more or less related to *equilibrium*. Before proceeding to consider stability further, therefore, it will be helpful if you understand neutral equilibrium, stable equilibrium, and unstable equilibrium.

Neutral equilibrium

If a steel ball is placed on a hard flat level surface, as in Figure 102 (*a*), it will remain at rest unless displaced. If given a slight push, it will roll in the direction in which it was pushed. If placed in a new position, it will remain there. The ball when at rest is said to be in *neutral equilibrium*.

Stable equilibrium

If the ball is placed in a spherical bowl, as in Figure 102 (*b*), it tends to remain at the lowest point of the bowl. If given

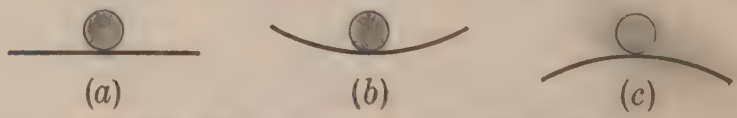


FIG. 102. Neutral, stable, and unstable equilibrium.

a slight *displacement* (given a push or placed in a different position in the bowl), it will roll back to its original position. It may *oscillate* (swing back and forth) awhile, but eventually it will come to rest. The ball when at rest in the bowl is said to be in *stable equilibrium*. An object in stable equilibrium may be said to have a *restoring tendency*.

Unstable equilibrium

If the ball is placed on a convex surface, as in Figure 102 (*c*), it will remain at rest if balanced at the exact point where the surface is level. But if the ball is given a slight displacement, it will roll away from the original position with increasing speed. The ball when balanced and stationary in this case is said to be in *unstable equilibrium*.

Restoring tendency in a plane

A plane may have characteristics that make it act, while flying, like a ball in stable, or in neutral, or in unstable equilibrium. In general, the designer strives to give a plane the characteristics of stable equilibrium. That is, he tries to design it so that if in straight and level flight it has been disturbed by gusts of wind that cause it to yaw, pitch, or roll slightly, it tends to return to the attitude of straight and level flight. To the extent to which the designer succeeds he may be said to give the plane restoring tendencies.

Damping tendency

Referring to Figure 102 (*b*), you can see that if the ball and the bowl have hard smooth surfaces, a displacement of the ball may cause it to oscillate for a considerable time. If moved one inch to one side of the low point, it may roll right through the low point and keep on till it is almost an inch away on the other side, then swing back and forth as it dies down, like a pendulum.

If a little molasses is placed in the bowl, more force will be

required to displace the ball; and when displaced it will oscillate more slowly and come to rest with fewer oscillations, because the molasses resists its motion in either direction.

Similarly in Figure 102 (*a*), if the flat surface were covered with a coating of molasses the ball would offer more resistance to a push and would promptly cease rolling.

In these cases the molasses is called a *damping fluid* and the ball is said to have a *damping tendency*. In the first case there is a damping tendency in addition to a restoring tendency. In the second case there is a damping tendency only.

STABILITY WITH REFERENCE TO YAW

Damping tendency by the fin

A damping tendency is given to a yawing displacement of an airplane by the stationary vertical fin (shown in Figure 103). We may think of the fin as the stationary part of the rudder, or we may think of the rudder as the movable part of the fin.

Let us say we are flying in a straight line and a gust of wind gives the plane a slight rotation on its vertical axis in a clockwise direction (yaw to the right). The rotation is promptly stopped by the fin, because while a plane is rotating on a vertical axis in a clockwise direction the air is striking the left side of the fin at a slight angle. This causes pressure on that side of the fin, which resists the rotation.

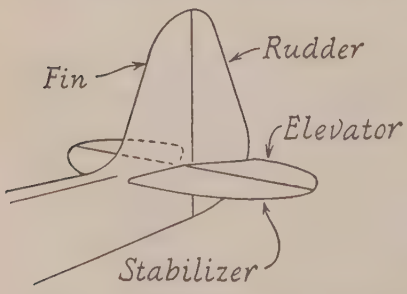


FIG. 103. Tail surfaces of a plane.

This retardation to yawing is known as the *weather-vane effect* of the fin. Stability with reference to yaw is some times called *directional stability*.

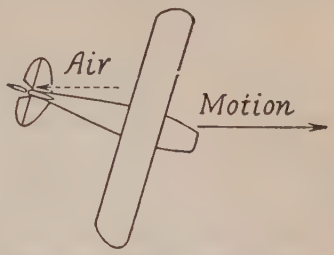


FIG. 104. How a fin contributes to stability with reference to yaw.

The change in direction of motion of the plane always lags slightly behind its change of direction of pointing; hence, after a slight yawing displacement of a plane that is heading and moving eastward, there will generally be a brief moment when the plane is moving eastward but is heading slightly to the south of east, as shown exaggerated in Figure 104. The plane is then momentarily skidding; and during that moment, since we assume that the turning has stopped but the excess pressure on the left side of the fin still persists, there is necessarily a tendency for the plane to be turned partially back to the left. That is, there is a momentary restoring tendency in the fin.

But this restoring tendency is slow in developing and is lost when the plane stops skidding and assumes flight in the direction in which it is then pointing. Hence the restoring tendency is not complete, and the plane is left heading and flying in a direction slightly different from the original direction.

It is impossible to construct a plane so that it has a complete restoring tendency *as to yaw*. A plane can hold a given heading automatically only with the help of a complicated connection between the controls of the plane and an instrument such as the directional gyro described later. In the absence of such an automatic steering instrument the plane must be restored to the original heading by the rudder moved by the pilot.

You will understand also that the vertical sides of the fuselage behind the center of gravity act in the same way as the fin. They also have a weather-vane effect. The sides of the fuselage in front of the center of gravity act in the

opposite direction, tending to make the plane unstable in yaw; but since more of the fuselage is behind the center of gravity than is in front of it, this excess behind the center of gravity helps to stabilize the plane as to yaw.

Sweepback

Another means of obtaining stability with reference to yaw is through *sweepback;* that is, a wing construction, as shown in Figure 105, in which the leading edges slant backward

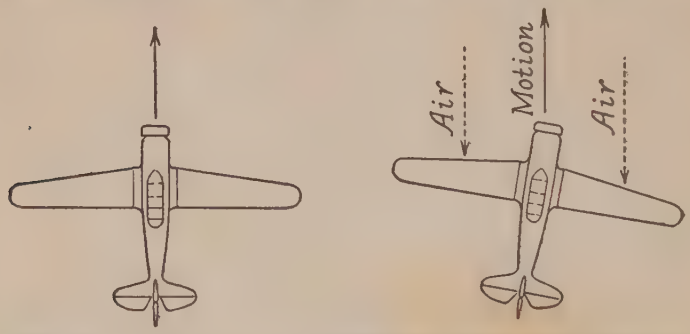


FIG. 105. How sweepback contributes to stability with reference to yaw.

toward the wing tips. A damping tendency is obtained by sweepback as follows: If the plane is yawed slightly by a gust of air — to the right, let us say — the left wing is presented more nearly perpendicularly to the relative wind, and the right wing less perpendicularly. This gives the left wing more drag than the right wing and retards the left wing till the right wing catches up, when the drag is again equal on the two wings. During this time the plane will have acquired a lasting yaw to the right and the original heading can be restored only with the rudder, as explained.

As in the case of the fin, sweepback affords a momentary restoring tendency which reduces the initial displacement in yaw but does not wholly restore the plane to its original heading.

STABILITY WITH REFERENCE TO ROLL

Stability with reference to roll is provided by what is called *dihedral* of the wings. (See Fig. 106 (*a*).) Note how the two wings come together to form a slight V or angle. This is called *dihedral*. In solid geometry an angle formed by two planes is called a dihedral angle; but, whereas in solid geometry the dihedral angle between two planes meeting at a line is measured by an arc between the planes as shown at *C* in Figure 106 (*b*), in aircraft it is customary to measure dihedral by the angle each wing makes with the lateral axis as shown at *d*. This means that the greater the angle *d*, the greater the dihedral.

The manner in which dihedral produces stability is as follows: If a momentary gust of wind blows the plane into a

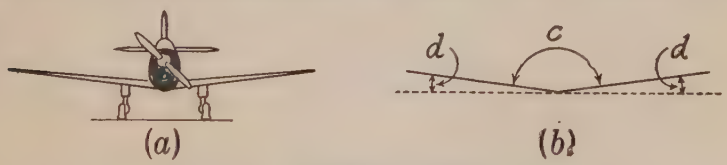


FIG. 106. Dihedral in airplane wings.

banked position, the plane will turn slightly and sideslip slightly. The sideslip results in an increase of angle of attack of the lower wing. This wing then has greater lift than the upper wing and is lifted until the plane is level.

Since a slight turning has been taking place during the banking, the plane when returned to level will be pointing in a slightly different direction from what it was before.

Dihedral therefore affords complete restoring tendency such as exists in a pendulum. A restoring tendency alone always tends to cause oscillation, since the momentum of restoring motion builds up like the velocity of a pendulum and, as was explained, tends to carry the motion past the point at which the restoring tendency ceases (corresponding to the vertical position of a pendulum).

U. S. Army Air Corps

FIG. 107. One of the fastest army pursuit planes, a Bell. Notice how the wing angles up slightly from root to tip. This angle is called *dihedral.* The plane has a tricycle landing gear; the single engine is mounted behind the pilot, and the propeller is driven by a long drive shaft.

There is a damping tendency with reference to roll, present in the wings of all planes, whether there is dihedral or not. This is because of changes in angle of attack.

If a plane is flying level and some force (even that produced by the ailerons) tends to roll the plane to the right, let us say, the angle of attack of the right wing is increased, giving it more lift; and the angle of attack of the left wing is decreased, giving it less lift. The excess lift of the right wing over that of the left resists rolling to the right and therefore constitutes a damping tendency as to roll. This is true regardless of whether the rolling is *from* a level position or *back to* a level position.

This damping tendency therefore prevents or retards the oscillation that might occur through the restoring effect of the dihedral.

Parasol stability

Another method of obtaining stability with reference to roll is by having the wings above the center of gravity (center of weight) as in a high-wing airplane. If you were to throw off the roof of a tall building an open parasol with a stone attached to the end of the handle, the stone would tend to bring the handle down and cause it to take a vertical attitude, with the stone at the bottom.

Comparably, a plane with most of its weight below the wings tends to remain level. This tendency is known as *parasol stability* or *keel effect.* It is a complete restoring tendency as to roll, the same as dihedral.

Stability with reference to roll is sometimes called *lateral stability*.

Position of wings

Planes are classified roughly into four kinds: *low-wing*, *mid-wing*, *high-wing*, and *parasol-wing* planes, according to whether the wings are attached to the bottom of the fuselage, the middle of the side, the top of the fuselage, or above the top of the fuselage and held to the fuselage by struts. In general, the lower the wing the greater the dihedral necessary for stability.

STABILITY WITH REFERENCE TO PITCH

Stability with reference to pitch is sometimes called "longitudinal stability"; but this term may be slightly misleading because stability with reference to pitch is stability with reference to rotation not on the longitudinal but on the lateral axis, and it has no more to do with the longitudinal axis than does the so-called directional stability.

A plane in straight-line flight is stabilized with reference to pitching by a stationary horizontal surface or surfaces at the tail of the plane, called the *stabilizer* (Fig. 103). It is the stabilizer to which the elevators are hinged. We might think of the stabilizer as the stationary part of the elevators; or we might think of the elevators as the movable part of the stabilizer. The stabilizer, although spoken of as one part,

U. S. Army Air Corps

Fig. 108. A low-winged pursuit plane, a North American. In this plane the engine is mounted ahead of the pilot, as is conventional. The landing gear is also conventional. The engine is an Allison. The wings have dihedral.

is really in two sections, one on each side of the fuselage. One elevator is attached to each portion of the stabilizer.

If a plane is in straight and level flight and a gust of air momentarily blows the tail slightly upward, there is a slight excess of pressure on the upper surface of the stabilizer, as shown in Figure 109. This pressure retards the upward

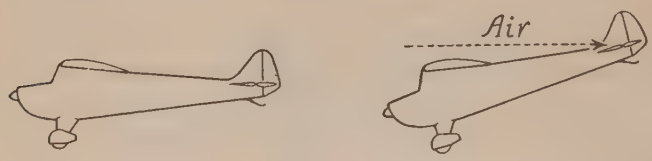


FIG. 109. How the stabilizer contributes to stability with reference to pitch.

motion of the tail and promptly stops the downward pitching. It is a damping tendency only and leaves the plane in a position pointing slightly downward.

Similarly, if a gust of wind blows the tail down, upward pitching is retarded by the force of air on the underside of the stabilizer, but the plane is left pointing upward.

Also the top and bottom surfaces of the fuselage extend farther back of the lateral axis (center of gravity) than they do forward, and hence the rear portions of those top and bottom surfaces assist the stabilizer in this damping tendency.

Restoring tendency in pitching

Figure 110 shows a plane in straight level flight. The line *CLS* represents the longitudinal axis of the plane from the center of gravity *C* to a point *S* on the stabilizer. Point *L* represents the center of lift.

Many light planes are constructed nowadays so that the lift of the wings (*L*) is to the rear of the center of gravity (*C*); in other words, so that the center of gravity of the plane (*C*) is in front of the center of lift (*L*) of the wings. This makes the plane "nose heavy" and requires that there be a slight

downward pressure of air on the stabilizer in order to balance the plane and keep the nose from pitching downward. It is as if the line *CLS* were a lever with an upward force at *L* and two downward forces balancing each other, one a strong force at *C* (weight of the plane) and the other a much lesser force at *S* (downward pressure of air on the stabilizer). You can see that if a bar were suspended at *L* with a heavy weight hanging on it at *C*, it would take some downward pressure at *S* to keep the lever in balance.

Now it so happens that even though the stabilizer of a plane is level when the plane is in level flight, there is a *downwash* of air from the wings. This downwash strikes the top of the stabilizer and produces a downward pressure which at a certain speed will be just enough to balance the "lever." The faster the plane is flying, the greater this downwash and the greater is the pressure on the upper surface of the stabilizer.

It is apparent, therefore, that if for any reason the speed of the plane is reduced, the downwash of the wings is reduced

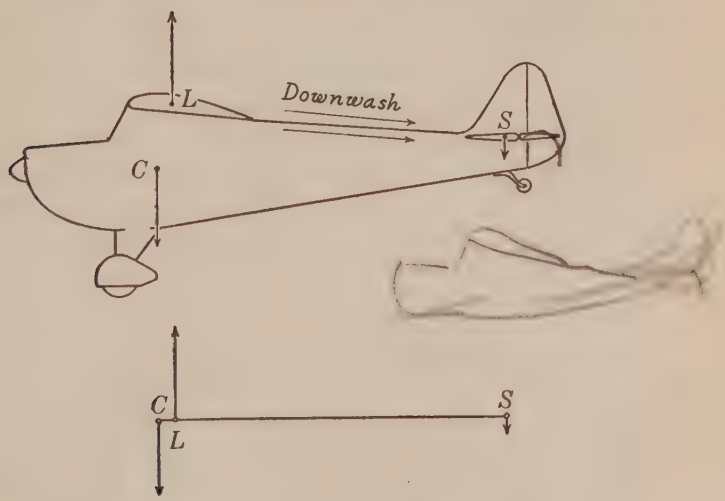


FIG. 110. The balance of vertical forces acting on a plane.

and the force at S becomes insufficient to hold the stabilizer down. It is as if the force at S on the lever in Figure 110 were allowing the force of gravity (at C) to pull the nose down.

If a gust of wind should in some manner cause the plane to pitch down slightly, the plane if left to itself will tend immediately to pick up speed, since a plane can fly "downhill" faster than on a level with the same power. This excess speed causes excess downwash (greater than normal), and this excess pressure on the top of the stabilizer tends to bring the plane back to level.

Similarly, if a gust of wind should in some manner lift the nose of the plane slightly, it will slow its speed and thus cause a diminished pressure on the top of the stabilizer. The weight of the plane then pulls the nose down and restores the plane eventually to level flight.

Here we have, then, a complete restoring tendency for stability in regard to pitching.

Effect of change in power

If a plane is in level flight and the power of the engine is reduced a little, the downward force of air on the stabilizer is reduced and the plane noses down slightly. It then picks up speed a little, just as an automobile would pick up speed on beginning a gentle down grade. This increased speed increases the pressure on the stabilizer enough to prevent the plane from nosing down more than a very little, and it therefore continues to descend slightly in a straight line at uniform speed.

Restoring the original engine power has the opposite effect. It first creates greater pressure on the upperside of the stabilizer, and this pushes the tail down. When the plane has reached a level position (as at first), the downhill-coasting effect is no longer present and the plane loses its excess forward speed. This causes the excess pressure on the top of the stabilizer to be lost and the tail no longer to

be pushed down. The plane remains level and continues its level flight as before.

Similarly, if when a plane is in level flight the power of the engine is increased, the excess blast of air on the top of the stabilizer pushes the tail down; but when the plane has reached a climbing position, its forward speed is reduced (since it takes more power to climb than to fly level). The reduction in forward speed, when sufficient to remove all the excess blast of air on the stabilizer, causes the tail to cease being pushed down farther and the plane continues to climb in a straight line.

Perhaps you can figure out how restoring the original power of the engine will cause the plane to cease climbing and to regain its level flying position. (The downward pressure on the tail is first reduced. Etc.)

Elevator tab

You can easily see how the balance of a plane, as shown in Figure 110, can be disturbed by a change in the number of passengers, amount of baggage, fuel, etc., which would affect the position of the center of gravity. The pilot needs some method of compensating for such a change. It is customary, therefore, to provide a *tab* in one of the elevators, amounting to a small aileron set in the trailing edge of the elevator, adjustable from the cockpit, usually by turning a small crank overhead.

If the pilot finds the plane "nose heavy," it means that he does not have enough downward force on the tail surfaces, as at *S* in Figure 110. In that case he can turn the crank so as to set the tab at a slight angle upward. This causes a slight additional downward aerodynamic force on the tail, causing the plane to become stable in the level position. If the plane is "tail heavy," the crank is turned in the opposite direction, the tab is thus depressed, and a slight aerodynamic force is added to the underside of the elevator.

This counteracts enough of the downward force on the tail to allow the plane to become stable in the level position.

Questions

1. What is meant by neutral equilibrium?
2. What is meant by stable equilibrium?
3. What is meant by unstable equilibrium?
4. What is static stability in a plane?
5. What is dynamic stability in a plane?
6. Which kind of stability is a restoring tendency? a damping tendency?
7. What is stability with reference to yaw?
8. What is the effect of the fin in producing stability?
9. What tendency does a fin produce?
10. What is meant by weather-vane effect?
11. How does the fin produce a partial restoring tendency?
12. Is complete restoring effect possible with reference to yaw?
13. What is sweepback?
14. How does sweepback contribute to stability?
15. What is dihedral?
16. How does dihedral contribute to stability? (What tendency does it produce?)
17. How is a damping tendency caused in regard to roll?
18. What is parasol stability?
19. What is keel effect?
20. What control surfaces affect stability with reference to pitch? How?
21. What kind of tendency do the elevators produce?
22. How is a restoring tendency in pitch achieved in airplane design?
23. How is a restoring tendency in pitch effected?
24. What effect is had when a plane in level flight is given added power? reduced power?
25. What effect is had when a plane in a climb is given reduced power? when a descending plane is given increased power?
26. What is the purpose of an elevator tab? How does it operate?

14

LIFT AND DRAG

YOU have already learned how the reaction of air upon a wing as it is forced through the air is thought of as divided into two components, *lift* and *drag*.

It is important that you understand how the lift and drag of a wing are affected by change of angle of attack, by change of wing area, by change of air density, by change of velocity of the wing through the air, and by change in the shape of the wing.

These and related facts will help you understand some very important characteristics of airplanes, such as —

(1) why a plane lands at a slow speed,

(2) why a plane must fly at different angles of attack at different altitudes,

(3) why a plane gains altitude more slowly at high altitudes,

(4) why a plane cannot climb indefinitely,

(5) why it takes more power to fly a circle than a straight line at a given speed,

(6) why it is dangerous to make a turn near the ground,

(7) why a plane cannot fly continuously at more than about 70° of bank, and

(8) why it is dangerous to try to fly a circle of too short a radius.

Wind tunnel

The lift characteristics of a wing of a given design are determined by putting a model of the wing in a wind tunnel,

subjecting it to a flow of air of known velocity and density, and measuring the force of lift.

A wind tunnel is merely a Venturi tube, as shown in Figure 111, made as large as practicable. The air is drawn through it by a propeller placed at the discharge end. The throat of the tube, where the velocity of air is greatest, is the experimental chamber in which the model is placed.

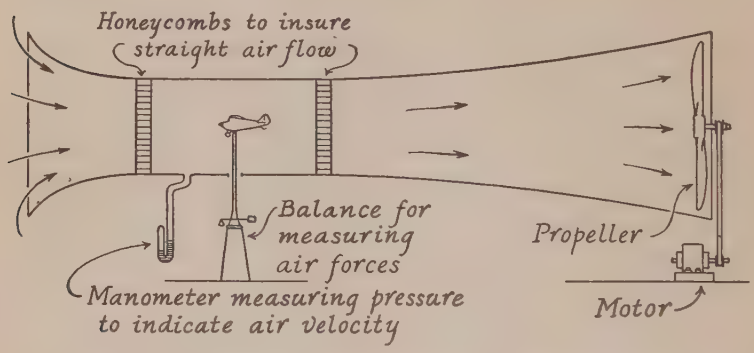


FIG. 111. Diagram of a wind tunnel. (See also Fig. 76.)

Lift varies in proportion to wing area

If two airplanes are exactly alike in shape and in every other respect except size, and if both are placed in an air stream of the same speed and density of air and at the same angle of attack of the wings, the larger plane will have the greater lift.

If the wing area (under surface) of one plane is double that of the other, the first plane will have double the lift of the second. If the wing area is three times as great in one plane as in the other, the lift will be three times as great, and so on. We say that the lift *varies directly in proportion* to the wing area.

PROBLEM 1. An airplane model has a wing span (length) of 5 feet, and a mean chord (width) of .5 foot. It shows a

lift of 2 pounds under given wind-tunnel conditions. What lift would a plane of similar design have with 138 square feet of wing area?

SOLUTION. 1. Find the wing area of the model. ($5 \times .5 =$ 2.5 square feet)

2. Find the lift for one square foot of wing area. (2 pounds $\div$ 2.5 = .8 pound of lift per square foot)

3. Multiply the lift per square foot by the number of square feet of wing area in the full-size plane. ($138 \times .8$ pound = 110.4 pounds, total lift)

EXERCISE 1. In Problem 1 change the wing span of the model to 6 feet, and solve the problem.

PROBLEM 2. Which model shows the better lift characteristic, model A which has 11 square feet of wing area with a lift of 9 pounds, or model B which has 16 square feet of wing area with a lift of 13 pounds, under the same conditions?

SOLUTION. 1. Find the lift for one square foot for model A. (9 pounds $\div$ 11 = .82 pound per square foot)

2. Find the lift for one square foot for model B. (13 pounds $\div$ 16 = .81 pound per square foot)

3. Compare the two lifts per square foot. (Model A shows a slightly superior lift characteristic, .82 as against .81 pound per square foot under the given conditions.)

EXERCISE 2. In Problem 2 change the lift of model A to 8 pounds and the lift of model B to 12 pounds and solve.

EXERCISE 3. An airplane model shows a lift of 4.5 pounds in a wind tunnel under known conditions of air speed, air density, and angle of attack. Its wing span is 7 feet and the mean chord is .8 foot. What lift would a plane of similar design have under the same conditions if the wing had a wing area of 118 square feet?

EXERCISE 4. Model A shows a lift of 9.4 pounds with a wing area of 12.2 square feet. Model B shows a lift of

14.8 pounds with a wing area of 18.1 square feet, under the same conditions of air speed and air density. Which model has the better lift characteristic?

Lift varies as the square of the velocity of the air

When the velocity of air past a wing is doubled, the lift of the wing is made four times as great. If the velocity of air is made three times as great, the lift is nine times as great, and so on.

The correspondence between lift and velocity is shown further in the following table.

Velocity	Lift
1 foot per second	a certain amount
2 feet per second	4 times as great
3 feet per second	9 times as great
4 feet per second	16 times as great
5 feet per second	25 times as great
6 feet per second	36 times as great
7 feet per second	49 times as great
8 feet per second	64 times as great
9 " " " Etc.	81 " " "

We see that the number in the lift column is the square of the number in the velocity column. We say that the lift *varies directly as the square of the velocity* of the air, or as the square of the velocity of the wing through the air.

Suppose we know that the lift at 4 feet per second air speed is so-and-so. We see from the above table that to find the lift at one foot per second we should have to divide the amount of lift at 4 feet per second by 16, or by 4^2. To find the lift at one foot per second from the lift at 5 feet per second we should have to divide by 5^2.

Changing "velocity" to "air speed"

It is convenient to use Velocity (V) to mean feet per second only, and to use Air speed (A) to mean miles per hour only.

Using the letters in this way, we then have —

$$\text{Air speed} = \tfrac{3600}{5280} \text{ of Velocity, or}$$
$$A = .682\ V$$

$$\text{Also Velocity} = \tfrac{5280}{3600} \times \text{Air speed, or}$$
$$V = 1.467\ A$$

PROBLEM 3. A given airplane model shows a lift of 3.2 pounds in a wind tunnel when the velocity of air is 20 feet per second. What lift would it have if air speed were 80 miles an hour, other conditions being the same?

SOLUTION. Find the lift at one foot per second.

1. $V^2 = 20^2 = 400$
2. $\frac{1}{400}$ of $3.2 = .008$ pound (lift at one foot per second)

Find the lift at 80 miles an hour. First change miles an hour to feet per second ($V = 1.467\ A$).

3. $80 \times 1.467 = 117$ feet per second
4. $117^2 = 13689$ (Table of Squares and Square Roots, page 643)
5. $13689 \times .008 = 110$ pounds

The lift at 80 miles an hour is 110 pounds.

EXERCISE 5. Change the air speed in Problem 3 to 90 miles an hour and solve.

PROBLEM 4. Given an airplane model A showing a lift of 5.6 pounds at 15 feet per second air speed, and a model B of the same wing area showing a lift of 7.8 pounds at 19 feet per second air speed. Other conditions being the same, which has the better lift characteristic?

SOLUTION. Find the lift for one foot per second in each case and compare these lifts.

1. $15^2 = 225$
2. $\frac{1}{225}$ of 5.6 pounds $= .0249$ pound (lift of model A at one foot per second air speed)
3. $19^2 = 361$
4. $\frac{1}{361}$ of 7.8 pounds $= .0216$ pound (lift of model B at one foot per second)
5. Model A shows the better lift characteristic.

EXERCISE 6. Change the air speed for model A to 16 feet per second in Problem 4 and the lift of model B to 8.1 pounds and solve.

Scale effect

It should be explained that the lift does not vary *precisely* as the square of the velocity of air. Under some conditions the lift for a larger plane tends to be somewhat different from what would be obtained by the above method. This slight difference is called *scale effect.* We shall disregard scale effect in our problems.

EXERCISE 7. An airplane model shows a lift of 4.9 pounds in a wind-tunnel test in which the velocity of the air is 28 feet per second. What would be the lift of the same model plane with an air speed of 109 miles an hour, other conditions being the same?

EXERCISE 8. Airplane model A shows a lift of 10.4 pounds in an air speed of 40 feet per second. Model B shows a lift of 15.3 pounds in an air velocity of 50 feet per second, other conditions being the same. Which model has the better lift characteristic?

PROBLEM 5. A given airplane model shows a lift of 2.6 pounds in a wind tunnel at 20 feet per second air velocity. The wing area is 11.2 square feet. What will be the lift on a full-size airplane of similar design with a wing area of 124 square feet when the air speed is 111 miles an hour, other conditions being the same?

SOLUTION. Find the lift for one square foot of wing area at 20 feet per second, then at one foot per second.

1. 2.6 pounds ÷ 11.2 = .232 pound (lift per square foot)
2. $V^2 = 20^2 = 400$
3. .232 pound ÷ 400 = .00058 pound (lift per square foot at one foot per second)

Find the lift for the full-size airplane at one foot per second, then at full speed.

4. $124 \times .00058 = .072$ pound (lift at one foot per second)
5. 111 miles per hour $= 1.467 \times 111 = 163$ feet per second
6. $163^2 = 26569$
7. $26569 \times .072 = 1913$ pounds

The lift on the full-size airplane is 1913 pounds.

EXERCISE 9. In Problem 5, change the lift in the wind tunnel from 2.6 to 2.8 pounds and the velocity of air from 20 to 24 feet per second and solve.

Unit wing at unit speed

For convenience of reference we might use the term *unit wing* to refer to one square foot of wing area or a wing with an area of one square foot. Also we might use the term *unit velocity* to mean one foot per second. The lift of a wing of one square foot area at one foot per second would then be spoken of as the lift on a unit wing at unit velocity.

PROBLEM 6. Model plane A having a wing area of 6 square feet shows a lift of 2.7 pounds in a wind tunnel when the velocity of air is 30 feet per second. Model B with a wing area of 7 square feet shows a lift of 5.04 pounds with an air velocity of 40 feet per second. Other conditions being the same, which model shows the better lift characteristic? [1]

SOLUTION. Find the lift for a unit wing at unit air velocity for each model under the given conditions and compare these lifts.

1. 2.7 pounds $\div$ 6 $=$ .45 pound (lift for unit wing)
2. $.45 \div 30^2 = .0005$ pound (lift of model A for unit wing at unit air velocity)
3. 5.04 pounds $\div$ 7 $=$ .72 pound (lift for unit wing)

[1] NOTE TO THE INSTRUCTOR. The method used in these problems is not the simplest for the purpose, but it is chosen because later it helps give the student a clear understanding of the meaning and use of coefficients of lift and drag. Later the student will be taught the more economical methods of computing the effect of changes in weight, wing area, and the like.

4. $.72 \div 40^2 = .00045$ pound (lift of model B for unit wing at unit air velocity)

5. Model A is superior in lift. (.0005 pound as against .00045 pound)

EXERCISE 10. Change the lift of model A in Problem 6 to 3.1 pounds and the air velocity of model B to 37 feet per second, and solve.

EXERCISE 11. A given airplane model shows a lift of 1.25 pounds in a wind-tunnel experiment in which the velocity of the air is 25 feet per second. The model has a wing span of 6 feet and a mean chord of .7 foot. What will be the lift on a full-size airplane of the same design with a wing span of 36 feet and mean chord of 4.2 feet, at 120 miles an hour?

EXERCISE 12. Model plane A with wing area of 7.2 square feet shows a lift of 7.3 pounds when the air velocity is 45 feet per second. Model plane B with a wing area of 8.4 square feet shows a lift of 12.2 pounds when the air velocity is 55 feet per second. Which has the better lift characteristic under the given conditions?

Drag varies with wing area

If two planes have exactly the same shape and one plane has twice as much wing area as the other, it will also present twice as much wing surface to the onrushing air and it will have twice as much drag as the other plane. Drag varies directly in proportion to the wing area, other conditions being the same.

Drag varies as the square of the velocity

Other conditions being the same, drag varies as the square of the velocity of the air in exactly the same way that lift does.

The drag of a plane of given wing area and at a given air speed can be determined by means of a wind-tunnel test, just as lift can be determined.

PROBLEM 7. A wind-tunnel test shows that the drag on a model plane of 15 square feet wing area is .72 pound in an air velocity of 40 feet per second. What will the drag be on a full-size plane of identical design having a wing area of 150 square feet and being flown at an air speed of 120 miles an hour, other conditions being the same?

SOLUTION. Find the drag of a similar plane having unit wing area, then for a similar plane of unit wing area at unit velocity.

1. .72 pound ÷ 15 = .048 pound (drag per unit wing area)
2. $V^2 = 40^2 = 1600$
3. .048 pound ÷ 1600 = .00003 pound (drag of unit wing at unit velocity)

Find the drag for the new wing area, at unit velocity, then at velocity of "new" plane.

4. 150 × .00003 pound = .0045 pound (drag of new wing at unit velocity)
5. $V = 1.467 \times 120 = 176$ feet per second
6. $V^2 = 176^2 = 30976$
7. 30976 × .0045 pound = 139.4 pounds

The total drag of the "new" plane is 139.4 pounds.

EXERCISE 13. In Problem 7 change the wind-tunnel drag from .72 pound to .85 pound and change the "new" speed to 130 miles per hour and solve.

PROBLEM 8. The drag of airplane model A with a wing area of 6 square feet is .162 pound at an air velocity of 30 feet per second. The drag of model B with a wing area of 8 square feet is .36 pound at an air velocity of 40 feet per second. Which model has the better drag characteristic? The better one is, naturally, the one with least drag under similar conditions.

SOLUTION. Find the drag of each model for unit wing area and unit air velocity, and compare these drags.

1. .162 pound ÷ 6 = .027 pound (drag for unit wing area)
2. .027 pound ÷ 30^2 = .00003 pound (drag of model A for unit wing area at unit air velocity)

3. .36 pound ÷ 9 = .04 pound (drag for unit wing area)

4. .04 pound ÷ 40^2 = .000025 pound (drag of model B for unit wing area at unit air velocity)

5. Model B shows less drag, under unit conditions, hence the better drag characteristic.

EXERCISE 14. In Problem 8, assume the wing areas to be 7 and 10 square feet instead of 6 and 9. Solve.

Lift varies with air density

Lift varies as the density of the air through which the plane is flying. If we fly at an altitude in which the air is only three fourths as dense as at sea level, the lift of the wings is only three fourths as great — at the same speed. If we fly where the density of the air is only one half as great as at sea level, the lift is only one half as great — at the same speed; and so on. We say that the lift varies directly as the density of the air.

Limit to altitude of flying

The above relation between lift and air density, by the way, is one reason that airplanes cannot climb indefinitely. Air at 22,000 feet, as we shall see later, is only half as dense as air at sea level. Loss of lift through decrease in density of the air can be made up for in part by increased speed, but not indefinitely because of the limitations of power. Density of air decreasing with altitude therefore sets a limit on flying altitude.

The determination of the maximum altitude at which a given plane can fly is explained on pages 239 and 240.

Unit of density

By the *density* of a body we mean the number of units of mass of the body there are in one cubic foot of it. By *mass* is meant quantity of matter.

Slug

The unit of mass is called a *slug*. A slug is an amount of matter that weighs approximately 32.2 pounds.[1]

Air of unit density

For convenience in discussing the density of air it will be convenient to speak of *air of unit density*. This means imaginary air weighing about 32.2 pounds per cubic foot!

It is possible for air to weigh that much, but it would have to be under terrific pressure (about 3.2 tons per square inch). Air of unit density is about half as dense as water; as to density it would be like very light oil. Of course no airplane will be called upon to fly in such thick air. But it is convenient to use the idea of unit density in reasoning and computation.

Density of air

Water weighs 62.4 pounds per cubic foot; hence water has a density of about 2 slugs per cubic foot. Air, of course, is far less dense than water. At sea level under standard conditions (59° F. or 16° C.), air has a density of .002378 slug per cubic foot.[2]

Relation between density and altitude

In order to study the effect of altitude on lift we need to know the relation between density of air and altitude. This

[1] For mathematical convenience the unit of mass is taken as the amount of matter that weighs 32.2 pounds at a point on the earth's surface where the force of gravity is such as to cause a body falling freely in a vacuum to accelerate its velocity at the rate of 32.2 feet per second every second.

Near the equator the force of gravity causes an acceleration of only about 32.1 feet per second every second. There a slug weighs only about 32.1 pounds.

[2] It would be convenient if we had a name for $\frac{1}{1,000,000}$ of a slug (like *millimeter*, which means $\frac{1}{1000}$ of a meter). If we called such a unit a milslug, we could say that air had a density of 2378 milslugs per cubic foot. But lacking such a unit we must get along with a decimal point and a few zeros.

relation is shown in the following table. You will see that the density of air *varies inversely* with altitude — the higher the altitude the less the density, though *not* inversely in *proportion*.

The approximate intermediate values at the foot of the table are given for convenient use in problems.

TABLE 1

SHOWING THE RELATION BETWEEN DENSITY AND ALTITUDE

ALTITUDE (IN FEET)	DENSITY (IN SLUGS PER CUBIC FOOT)
50,000	.000361
40,000	.000582
30,000	.000889
20,000	.001267
15,000	.001496
10,000	.001756
9,000	.001812
8,000	.001869
7,000	.001928
6,000	.001988
5,000	.002049
4,000	.002112
3,000	.002176
2,000	.002242
1,000	.002309
0	.002378

APPROXIMATE INTERMEDIATE VALUES

ALTITUDE	DENSITY
9,200	.0018
7,500	.0019
5,800	.0020
4,200	.0021
2,600	.0022
1,100	.0023

Lifts at varying altitudes

In order to compare lifts of an airplane wing at different altitudes, or densities, it is convenient to be able to find the lift of the same wing in air of unit density and of other densities.

Let us forget for a moment how thick air of unit density is. We know that in regard to a given wing the following is true:

Lift in air of 1 slug per cubic foot = a certain amount
Lift in air of 2 slugs per cubic foot = 2 times as much
Lift in air of 3 slugs per cubic foot = 3 times as much, etc.

Hence, to find the lift in air of 4 slugs per cubic foot we would multiply the lift in air of unit density by 4.

Remember, then, that when you know the lift in air of unit density, to find the lift in "new" air of a given density *multiply the lift in air of unit density by the number of slugs per cubic foot in the "new" air.*

Also, if we know the lift of a wing in air of a density of 3 slugs per cubic foot, to find the lift in air of one slug per cubic foot — that is, in air of unit density — we would *divide by 3.*

Remember, then, that *to find the lift of a wing in air of unit density, divide the actual lift by the number of slugs per cubic foot in the existing air.*

PROBLEM 9. If an airplane has a lift of 1200 pounds at sea level (0 feet altitude), what will its lift be at the same air speed at 5000 feet?

SOLUTION. 1. Find the lift of the same plane in air of unit density. (Air at 0 feet altitude has a density of .002378 slug per cubic foot. See Table 1.)

1200 pounds ÷ .002378 = about 504,600 pounds[1] (theoretical lift at given air speed in air of unit density)

[1] The true quotient is 504,625.68, but it is sufficient in a calculation such as this to get the first four figures correct to the nearest fourth figure (nearest hundred in this case) and write zeros for the rest of the quotient.

2. Find the lift in air at the density of the new altitude. (Air at 5000 feet has a density of .002049 slug per cubic foot.)

.002049 × 504,600 pounds = 1034 pounds (lift at 5000 feet)

EXERCISE 15. Find the lift of the same plane at the same air speed at 10,000 feet, at 15,000 feet, at 20,000 feet.

Increased densities used in wind tunnels

Sometimes the air in a wind tunnel is put under pressure to make up in part for lack of high velocity. Greater pressure gives greater density of air.

PROBLEM 10. Airplane A tested under normal air pressure (.002378 slug per cubic foot) shows a lift of 1000 pounds at a given air speed. Airplane B, having the same wing area, tested at the same air speed in air at a pressure creating a density of .003 slug per cubic foot, shows a lift of 1410 pounds. Which has the better lift characteristic?

SOLUTION. Find the lift of each plane in air of unit density and compare these lifts.

1. 1000 pounds ÷ .002378 = about 420,500 pounds (lift of model A in air of unit density at same air speed)

2. 1410 pounds ÷ .003 = 470,000 pounds (lift of model B in air of unit density at same air speed)

3. Model B has the better lift characteristic.

EXERCISE 16. In Problem 10 change the lifts from 1000 and 1410 to 1100 and 1470 pounds, and solve.

Drag varies with air density

Drag varies directly with air density in exactly the same manner as lift.

PROBLEM 11. If the airplane in Problem 9 has a drag of 80 pounds at 1100 feet, what will its drag be at 5800 feet at the same air speed?

SOLUTION. First find the drag in air of unit density.

1. The density at 1100 feet is .0023 (Table 1).

2. 80 ÷ .0023 = about 34,800 pounds (drag in air of unit density).

Then find the drag at the new air density.

3. The density at 5800 feet is .0020.

4. .0020 × 34,800 = 69.6 pounds (drag at 5800 feet).

EXERCISE 17. In Problem 11 what would the drag be at 7500 feet? at 9200 feet?

Lift varies with angle of attack

For small angles of attack the lift increases as the angle of attack increases. That is, up to a certain angle (say 18° to 20°) the greater the angle of attack, the greater the lift in the same air velocity. At between 18° and 20°, or thereabouts, burble usually begins and thereafter the lift becomes less instead of greater when the angle of attack is further increased.

A common type of airfoil has zero lift at − 5° angle of attack. The lift increases about in proportion to the absolute angle of attack (measured from − 5°) up to about 18° angle of attack. Between 18° and 20° the lift remains about the same, but after 20° the lift drops off very suddenly.

Drag varies with angle of attack

Drag also increases as angle of attack increases, but in a different way from lift. Beginning with the no-lift angle of attack there is a little drag which increases slowly at first with increase in angle of attack, then more rapidly. Then at about 20° angle of attack, when burbling begins, the drag increases very rapidly with little increase in angle of attack.

COEFFICIENTS OF LIFT AND DRAG

Research on lift and drag

A great deal of experimenting has been done to find the shape of airfoil section and wing shape which will give the greatest lift and the least drag in proportion to the lift for a given angle of attack and a given size of wing.

In order to make comparisons between wings of different shapes and sizes, wings are compared in terms of what are called the *coefficient of lift* and *coefficient of drag*. Problem 12 will help you to understand the meaning of the coefficients.

PROBLEM 12. The lift shown by airplane model A with a wing area of 100 square feet is 864 pounds in an air velocity of 120 feet per second, in air of a density of .003 slug per cubic foot with wings at 2° angle of attack. The lift shown by airplane model B with a wing area of 150 square feet is 2765 pounds, in an air velocity of 160 feet per second, in air of a density of .004 slug per cubic foot, with wings at the same angle of attack. Which model has the better lift characteristic at 2° angle of attack?

SOLUTION. Find the lift of model A per unit wing area, per unit air velocity, per unit air density.

1. 864 pounds ÷ 100 = 8.64 pounds (lift per unit wing area)
2. 8.64 pounds ÷ 120^2 = .0006 pound (lift of unit wing at unit velocity)
3. .0006 pound ÷ .003 = .2 pound (lift of unit wing at unit velocity in air of unit density)

Do the same for model B.

4. 2765 pounds ÷ 150 = 18.43 pounds
5. 18.43 pounds ÷ 160^2 = .00072 pound
6. .00072 pound ÷ .004 = .18 pound

Since .2 pound is greater than .18 pound, model A shows the better lift characteristic at 2° angle of attack.

It is customary to use the Greek letter *rho* (ρ) to designate the number of units of density of a fluid; that is,

ρ = the number of slugs per cubic foot. Thus, when the density of a fluid is 2 slugs per cubic foot, $\rho = 2$ for that fluid. For air at sea level under standard conditions, $\rho = .002378$; at 2600 feet, $\rho = .0022$; and so on.

Coefficient of lift

The lift characteristic of a wing at a given angle of attack is customarily expressed in terms of what is called the *coefficient of lift* (represented by C_L).

The coefficient of lift for a given wing shape at a given angle of attack is the number of pounds of lift of a wing of that shape with unit area, at unit air velocity, and in air of one-half unit density.[1]

If we have the measure of total lift at given angle of attack under particular conditions of wing area, air velocity, and air density, we find the coefficient of lift for that angle of attack by means of the following formula:

$$C_L = \frac{L}{\frac{\rho}{2} S V^2} \qquad \text{(Formula for the coefficient of lift)}$$

in which —

C_L = coefficient of lift for the particular angle of attack,
L = total lift under the given conditions,
$\frac{\rho}{2}$ = $\frac{1}{2}$ the number of slugs of air per cubic foot,
S = wing area (surface) in square feet, and
V^2 = the square of the air velocity in feet per second.

[1] You may wonder why one-half unit of density was used instead of a whole unit. The coefficient of lift could just as well have been based on a whole unit of density or even better perhaps on $\frac{1}{1,000,000}$ unit of density which we suggested calling a milslug.

It happens that $\frac{1}{2}\rho V^2$ is a measure of pressure. It is the pressure in pounds per square foot which air of ρ slugs per cubic foot exerts at the center of a flat plate which the air is striking perpendicularly at V feet per second. At that precise point the air is stationary; hence all the velocity energy has been converted into pressure energy.

The coefficient of lift, then, is really the lift of a wing of given shape, with unit area, at unit air speed, in air not of unit density but of a density that produces *unit pressure* when all kinetic energy is converted to pressure energy.

The formula means $C_L = L \div (\frac{\rho}{2} \times S \times V^2)$. It would be read: The coefficient of lift equals the total lift divided by the product of one half the air density, the wing area, and the square of the velocity.

It is also the same as $C_L = L \div \frac{\rho}{2} \div S \div V^2$.

The coefficient of lift of model A in Problem 12 would be found this way:

$$C_L = \frac{L}{\frac{\rho}{2} S V^2} = \frac{864}{.0015 \times 100 \times 120^2} = .4$$

This value .4 is double the lift of unit wing area at unit air velocity at whole unit air density, which we found in Problem 12 to be .2 pound.

In giving a coefficient of lift we do not specify pounds but give the value only.

The coefficient of lift of model B would be found this way:

$$C_L = \frac{2765}{.002 \times 150 \times 160^2} = .36$$

If we *have* the coefficient of lift of a wing of a given type and wish to *find* the total lift of a wing of that type having a given wing area, at a given angle of attack, a given air speed, and in air of given density, we use the following formula:[1]

$$L = C_L \frac{\rho}{2} S V^2 \qquad \text{(Formula for total lift)}$$

in which —

L = total lift,
C_L = the coefficient of lift for the particular angle of attack,
$\frac{\rho}{2}$ = $\frac{1}{2}$ the number of slugs per cubic foot of the air flown through,
S = wing area, and
V^2 = the square of the air velocity.

[1] The formula means that $L = C_L \times \frac{\rho}{2} \times S \times V^2$.
Symbols placed side by side are intended to be multiplied together.

Coefficient of drag

There is a corresponding formula for expressing the drag of a wing at a given angle of attack in terms of the number of pounds of drag on a similar wing of unit area, at unit air velocity, in air of one-half unit density at that given angle of attack. This value is called the *coefficient of drag.* The formula for obtaining the coefficient of drag from the results of a given wind-tunnel experiment is as follows:

$$C_D = \frac{D}{\frac{\rho}{2} S V^2} \qquad \text{(Formula for the coefficient of drag)}$$

in which —

C_D = the coefficient of drag,
D = the total drag obtained in the experiment, and as before,
$\frac{\rho}{2}$ = $\frac{1}{2}$ the number of slugs of air per cubic foot,
S = wing area in square feet, and
V = the air velocity in feet per second.

If we have found the coefficient of drag of a given type of wing at a given angle of attack and wish to find the total drag on a similar wing of a given area and under given conditions of air velocity and density, we can use the following formula:

$$D = C_D \frac{\rho}{2} S V^2 \qquad \text{(Formula for total drag)}$$

in which the symbols have the same meaning as above.

Summary of formulas

For convenience of reference the formulas presented in Part II are listed at the end of Chapter 19, page 264.

The Clark Y airfoil

A common type of airfoil section is shown in Figure 112. It is called the *Clark Y airfoil.* The lift and drag coefficients

for various angles of attack of a Clark Y airfoil section are shown in Figure 112.

Angles of attack are represented by various vertical lines, as shown by the scale at the foot. The various values of coefficient of lift are shown by the curve on the left measured by the scale at the left. The coefficient of lift at 2° angle of attack, for example, is shown by the height of the point at which the curve cuts the vertical line above 2°. It is .5, as shown by the scale at the left. Values of the coefficient of drag are represented by the curve at the right measured by the scale at the right.

The left-hand curve shows that the coefficient of lift at − 4° is .07; at − 2° is .21; at 0° is .36; and so on. The right-hand curve shows that the coefficient of drag at − 4° is .01; at 0° is .017; at 2° is .025; and so on.

Exercise 18. What is the coefficient of lift of a Clark Y airfoil for 4°? 6°? 8°? 10°?

Exercise 19. What is the coefficient of drag of a Clark Y airfoil for 4°? 6°? 8°? 10°?

Table of lift and drag coefficients

For purposes of the problems in the following pages, let us use the following values of lift and drag for the Clark Y airfoil:

TABLE 2

Lift and Drag Coefficients of the Clark Y Airfoil

ANGLE OF ATTACK	COEF. OF LIFT	COEF. OF DRAG
0°	.36	.017
1°	.43	.021
2°	.50	.025
3°	.57	.029
4°	.64	.034

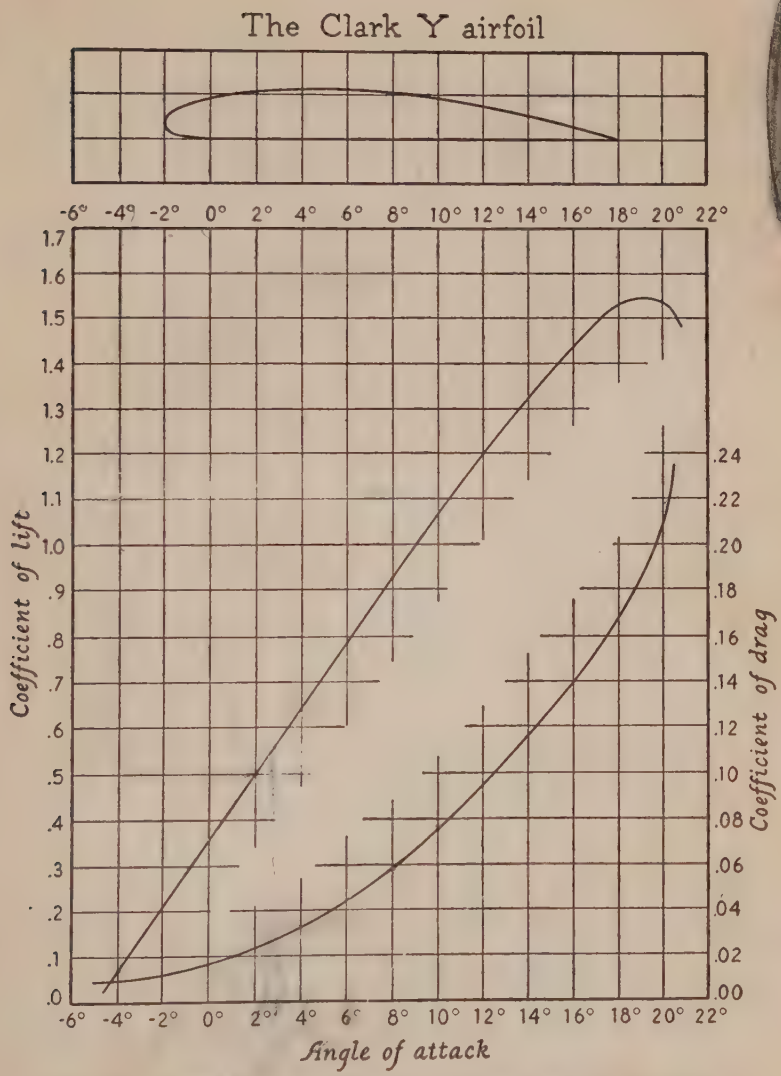


FIG. 112. Graph of the coefficients of lift and drag for the Clark Y airfoil at various angles of attack.

Note that at this point we are dealing with the lift and drag of only the wing of an airplane. Later in the book you will learn how to find the drag on the whole airplane.

We are now ready to compute the actual lift that would be obtained from wings of the Clark Y type for various wing areas, air velocities, air densities, and angles of attack.

PROBLEM 13. What is the lift of a Clark Y wing of 180 square feet wing area, flying at 80 miles an hour at 1100 feet altitude at 3° angle of attack?

SOLUTION. Solve the lift formula

$$L = C_L \frac{\rho}{2} S V^2$$

1. Find the coefficient of lift from the graph. C_L at 3° angle of attack = .57 (Table 2).

2. Find $\frac{\rho}{2}$. ρ, density at 1100 feet, from Table 1 = .0023; hence $\frac{\rho}{2}$ = .00115.

3. Find V^2. $V = 1.467 \times 80$ = about 117. $V^2 = 117^2 = 13689$.

$$\begin{array}{cccc} (C_L) & (\frac{\rho}{2}) & (S) & (V^2) \end{array}$$

4. $L = .57 \times .00115 \times 180 \times 13689 = 1615$ pounds.

The total lift on the wing at 3° angle of attack will be 1615 pounds.[1]

EXERCISE 20. What is the lift of a Clark Y wing of 170 square feet area, flying at 85 miles an hour, at an altitude of 4200 feet, at 1° angle of attack?

Velocity squared

Table 3 gives the velocities in feet per second in round numbers, with their squares and with the approximate corresponding air speeds in miles per hour. When air speeds found in this table are given in exercises, you may use the V and V^2 given in this table.

[1] It is sufficiently accurate in working the problems in this book to use the nearest whole number of feet per second when finding V^2. The answer will usually be correct within one per cent.

TABLE 3

APPROXIMATE VALUES OF AIR SPEED CORRESPONDING TO VARIOUS EVEN VALUES OF V AND V^2

APPROXIMATE AIR SPEED (IN MILES PER HOUR)	VELOCITY V (IN FEET PER SECOND)	V^2 (FEET PER SECOND)
68	100	10,000
82	120	14,400
95	140	19,600
109	160	25,600
123	180	32,400
136	200	40,000
150	220	48,400
164	240	57,600
177	260	67,600
191	280	78,400
205	300	90,000

PROBLEM 14. What is the drag of a Clark Y wing of 180 square feet area, flying at 90 miles an hour, at 2° angle of attack, at an altitude of 4200 feet?

SOLUTION. Solve the drag formula

$$D = C_D \tfrac{\rho}{2} S V^2$$

1. $C_D = .025$ (Table 2)
2. $\rho = .0021$ (Table 1), $\frac{\rho}{2} = .00105$
3. $S = 180$
4. $V = 1.467 \times 90 = 132$
5. $V^2 = 132^2 = 17424$
6. $D = .025 \times .00105 \times 180 \times 17424 = 82$ pounds

The drag in this case is 82 pounds.

EXERCISE 21. What is the drag of a Clark Y wing of 190 square feet flying at 100 miles an hour, at 3° angle of attack, at an altitude of 7500 feet?

EXERCISE 22. What is the lift on a Clark Y wing of 200 square feet area, flying at 123 miles an hour (see Table 3), at 4200 feet altitude, at 4° angle of attack?

EXERCISE 23. What is the drag in Exercise 20?

EXERCISE 24. What are the lift and drag on an Aeronca wing of the Clark Y type, of 170 square feet wing area, flying at 82 miles an hour, at sea level, at 1° angle of attack?

EXERCISE 25. A plane has a Clark Y wing of 292 square feet area. What is its lift at 2600 feet, at 2° angle of attack, the air speed being 205 miles an hour?

Göttingen 398 airfoil

A second type of airfoil, called the *Göttingen*[1] *398 airfoil*, is shown in Figure 113. The figure also shows the coefficients of lift and drag for this airfoil. It shows that the lift and drag for the angles of attack 0° to 4° are as follows:

TABLE 4

GÖTTINGEN COEFFICIENTS

ANGLE	C_L	C_D
0°	.43	.022
1°	.51	.025
2°	.58	.030
3°	.65	.036
4°	.72	.042

EXERCISE 26. What are the lift and drag on a Göttingen 398 wing of 200 square feet area, flying at 123 miles an hour (Table 3), at 4200 feet altitude, at 2° angle of attack?

Lift at various velocities

As an airplane gains speed over the ground and hence through the air while taxiing, the value of V in the lift formula is increasing. Let us investigate the change in lift that occurs as the velocity changes. To make it easy, we can use round numbers.

[1] Commonly pronounced "Gĕt′-ĭng-ĕn."

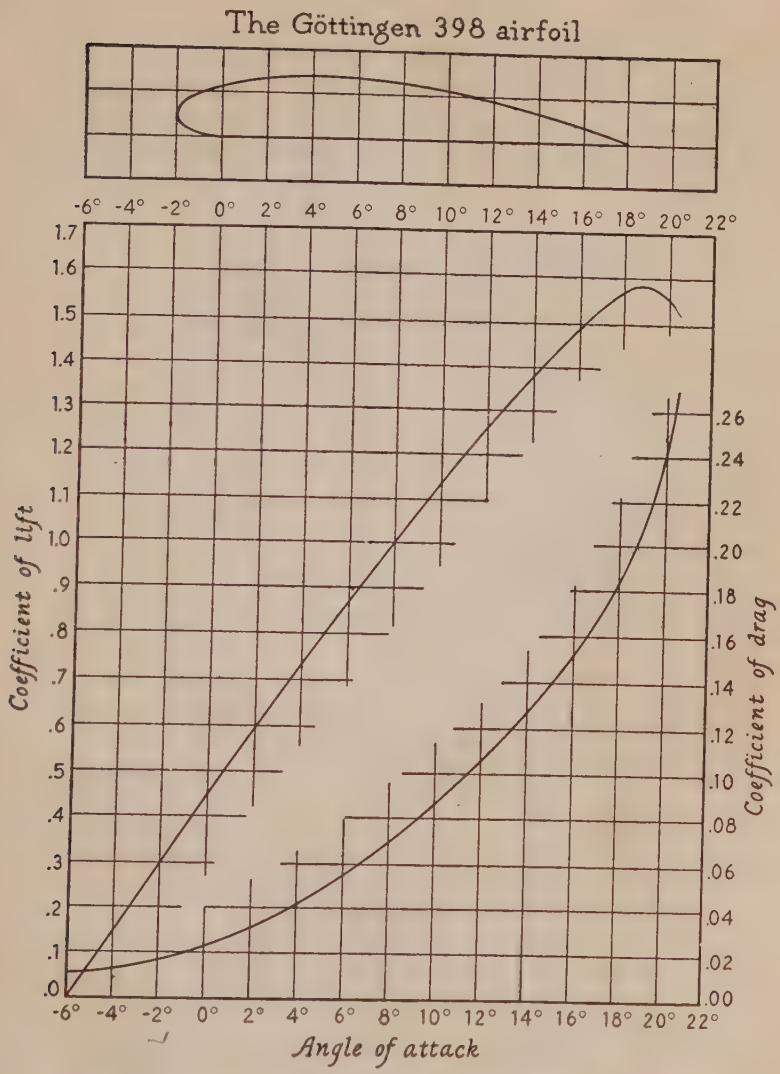


FIG. 113. Graph of the coefficients of lift and drag for the Göttingen 398 airfoil at various angles of attack.

PROBLEM 15. A plane is taking off from an airport at an altitude of 5800 feet above sea level. $\rho = .002$. It has a Clark Y wing of 200 square feet area, and an angle of incidence of 1°. (It flies normally at 1° angle of attack.) What lift will be created at 20, 40, 60, 80, 100, 120, 140, and 160 feet per second, assuming the wing to be at 1° angle of attack? [1]

SOLUTION. Solve the formula

$$L = C_L \tfrac{\rho}{2} S V^2$$

1. C_L for 1° (Clark Y) = .43
2. $\frac{\rho}{2} = .001$
3. $S = 200$
4. $C_L \times \frac{\rho}{2} \times S = .43 \times .001 \times 200 = .086$. We find this product first, as we shall need to multiply it several times.
5. V^2 (for 20 feet per second) $= 20^2 = 400$
6. $L = .086 \times 400 = 34$ pounds

The lift at 20 feet per second is 34 pounds.

7. Draw up a table as shown with column for V, V^2, and L.

TABLE 5

AMOUNTS OF LIFT AT VARIOUS VELOCITIES WHEN $\rho = .002$, $S = 200$, AND ANGLE OF ATTACK = 1°

V	V^2	L $(.086 \times V^2)$
20	400	34
40	1,600	138
60	3,600	310
80	6,400	550
100	10,000	860
120	14,400	1238
140	19,600	1686
160	25,600	2202

[1] Under normal conditions a plane would take off at a higher angle of attack in order to take off at slower speed and therefore less bumping over the ground.

8] Enter the various values of V and compute the corresponding values of V^2 and L (Table 5).

The solution shows that at 40 feet per second, 138 pounds of lift are created; at 60 feet per second, 310 pounds; etc., and at 160 feet per second, 2202 pounds of lift are created.

These values are plotted in Figure 114, with a smooth curve drawn through the points.

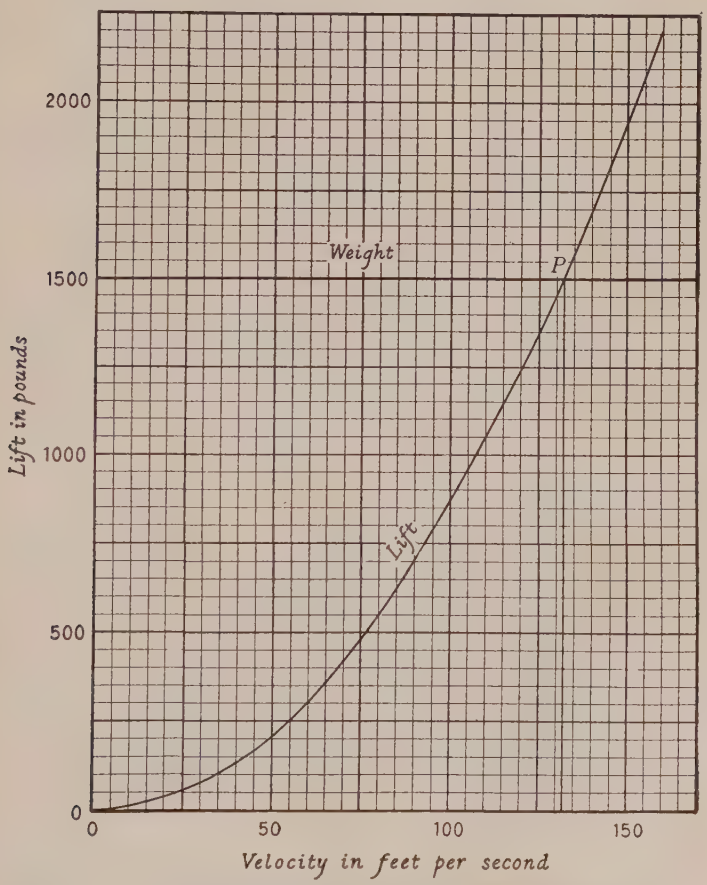


FIG. 114. Graph showing the increase in lift accompanying increase in velocity of a plane.

Lift for flying

We have seen how rapidly the lift of an airplane wing increases as the velocity of the airplane over the ground increases. Of course the plane will not rise from the ground until the lift equals the weight of the plane.

Let us say the plane weighs 1500 pounds. If we draw a line across the chart at a level representing 1500 pounds, we see that it crosses the curve at a point P representing a velocity of about 132 feet per second. This is about 90 miles an hour.

Exercise 27. What lift is created at 20, 40, 60, 80, 100, 120, 140, and 160 feet per second as a plane with Göttingen 398 wing of 300 square feet area takes off from an airport at 2600 feet, at 4° angle of attack?

Exercise 28. Draw a graph as in Figure 114 to represent the results of Exercise 27.

Exercise 29. By means of the graph of Exercise 28 find the velocity necessary to take off under the conditions given in Exercise 27, assuming the plane to weigh 1500 pounds.

Conversion graph

Figure 115 will be helpful in converting feet per second into miles per hour, and miles per hour into feet per second.

To find the approximate number of miles per hour corresponding to 132 feet per second —

(1) find a height representing 132 feet per second on the scale at the left,

(2) find the point on the graph at this height,

(3) find the point on the scale of miles per hour corresponding to this point, and

(4) read the number of miles per hour on the scale.

To convert miles per hour to feet per second, reverse the process.

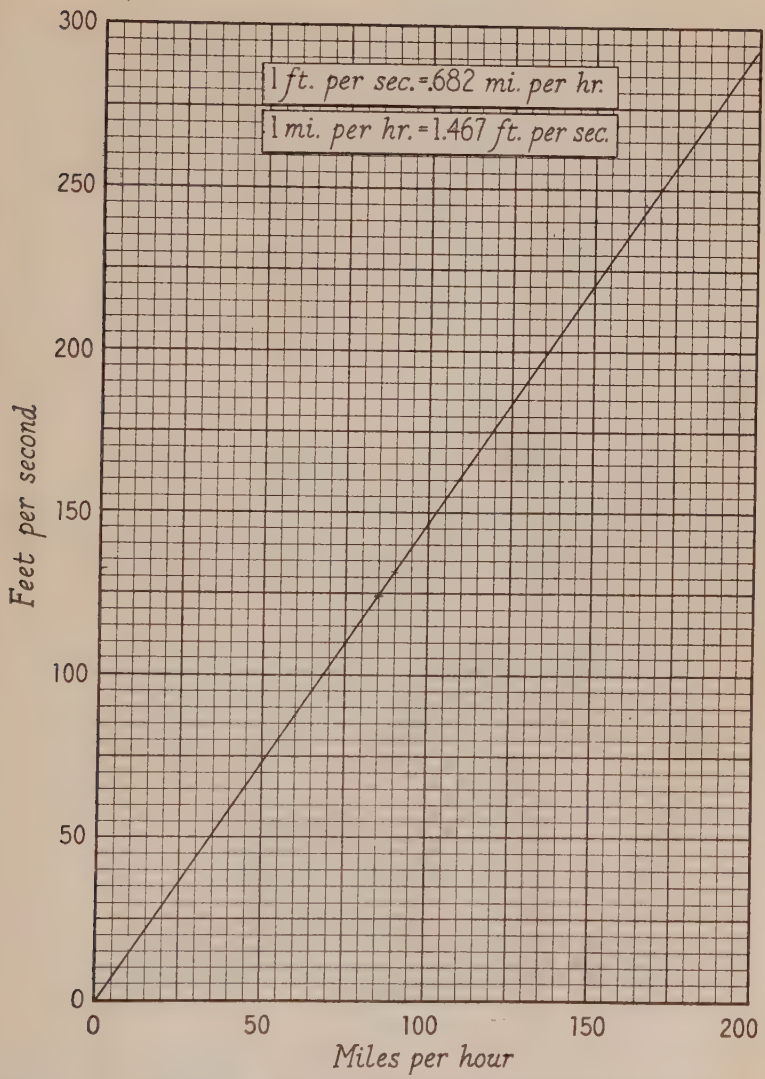


FIG. 115. Graph for converting miles per hour to feet per second, and vice versa.

Change of drag with velocity

It is of value to understand how the drag increases with increase in velocity. Let us investigate this.

PROBLEM 16. Find the drag of the wing of the plane in Problem 15 at the same velocities, altitude, and angle of attack. ($\rho = .002$. $S = 200$. $V = 20, 40, 60, 80, 100, 120, 140, 160$ feet per second.)

SOLUTION. Solve the formula $D = C_D \frac{\rho}{2} SV^2$

1. C_D (Clark Y at 1°) = .021
2. $\frac{\rho}{2} = .001$
3. $S = 200$
4. $C_D \times \frac{\rho}{2} \times S = .0042$
5. $V^2 = 20^2 = 400$
6. $D = .0042 \times 400 = 1.7$ pounds (1.68)

The drag at 20 feet per second is 1.7 pounds.

7. Draw up a table like Table 5, copy the values of V and V^2, and fill in the rest of the table. (See Table 6.)

TABLE 6

AMOUNTS OF WING DRAG AT VARIOUS VELOCITIES, WHEN $\rho = .002$, $S = 200$, AND ANGLE OF ATTACK = 1°

V	V^2	D ($.0042 \times V^2$)
20	400	1.7
40	1,600	6.7
60	3,600	15.1
80	6,400	26.9
100	10,000	42.0
120	14,400	60.5
140	19,600	82.3
160	25,600	107.5

Figure 116 shows these values of drag plotted on the same chart with the lift values. A new scale of drag is placed at the right in order that the curve will not be so nearly level.

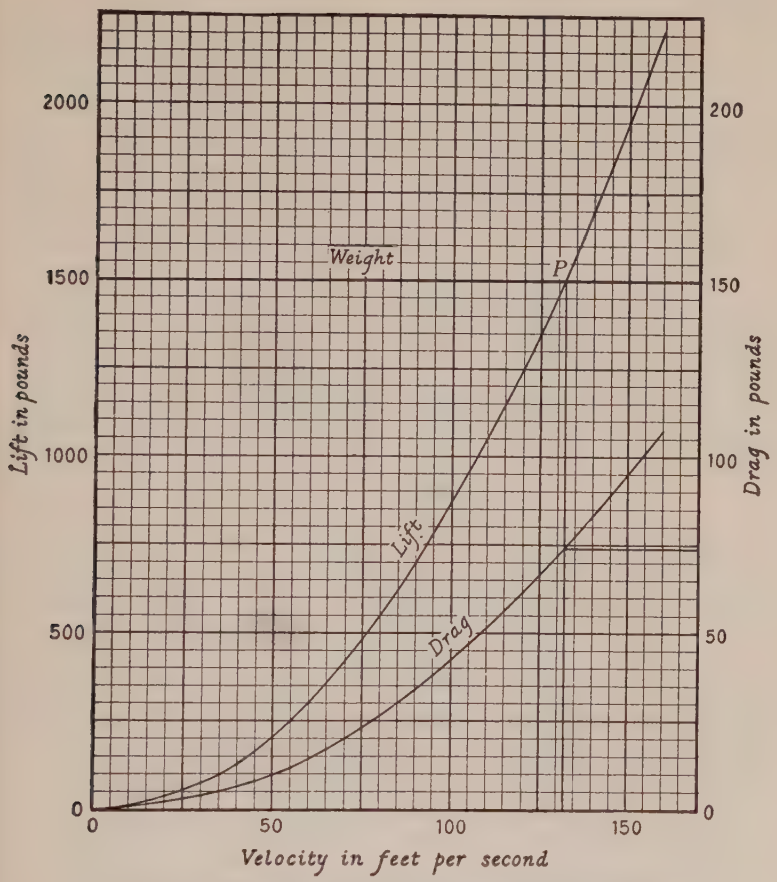


FIG. 116. Graph showing the increase in lift and drag accompanying increase in velocity.

Note that the drag curve cuts the take-off velocity (132 feet per second) at a height representing a drag of about 74 pounds.

Thrust equals drag

The pull of the propeller is called *thrust*. The thrust of the propeller must equal the drag. Hence the thrust needed

to overcome wing drag for the take-off in the plane of Problem 16, under the conditions given, is about 74 pounds.

EXERCISE 30. What is the wing drag created at 20, 40, 60, 80, 100, 120, 140, and 160 feet per second as a plane with Göttingen 398 wing of 300 square feet area as in Exercise 27 takes off at 2600 feet elevation at 4° angle of attack? You may put the values in a column at the right of your table for Exercise 27, if you wish.

EXERCISE 31. Draw the graph as in Figure 116. Put it on the same chart with the graph of the lift.

EXERCISE 32. What is the thrust necessary to overcome wing drag for a take-off under the conditions of Exercise 30, if the plane weighs 1200 pounds? 1400 pounds? 1600 pounds?

PARASITE DRAG

Resistance of flat plates to air flow

If we were to present a flat surface, as a piece of tin, at right angles to a stream of air moving at one foot per second, we should expect theoretically that the additional force on the surface presented would be equal to the kinetic energy of one cubic foot of air moving at one foot per second.

This energy or force, in pounds, equals $\frac{1}{2}$ the number of slugs of air in the cubic foot. That is, $F = \frac{\rho}{2}$ (for 1 square foot of flat plate and air moving 1 foot per second).

This means that theoretically we should expect the force of air moving against a flat plate at one foot per second at sea level to be one half of .002378 pound. At an altitude where $\rho = .002$ we should expect the force to be one half of .002 pound; and so on. That is, whatever the density of the air (ρ), we should expect the force under the unit conditions to be $\frac{1}{2}\rho$ pound.

However, because of burble and because the air rushing around the side of the plate affects air that would otherwise

flow past the plate undisturbed, the force of air on the flat plate is more than the kinetic energy of the air that strikes it. That is, experiments show that the force of air of ρ density, striking a flat plate of one square foot area at one foot per second, is about $1.28 \frac{\rho}{2}$ pounds.

Force varies with flat-plate area

Of course the force on two square feet is twice the force on one square foot; so if a flat plate has an area of a square feet, the force of the air at one foot per second is $1.28 \frac{\rho}{2} a$ pounds. That is, if $\rho = .002378$ (as at sea level) and the area (a) is 5 square feet, the force in pounds would be $1.28 \times \frac{1}{2}$ of $.002378 \times 5$ or about .0076 pound.

Force varies as the square of the velocity

The force against a flat plate varies as the square of the velocity of the air, or through the air, exactly as lift and drag; hence for V feet per second air flow

$$F = 1.28 \frac{\rho}{2} aV^2 \qquad \text{(Formula for drag of a flat plate)}$$

in which —

F = the force against the flat plate (its drag),
ρ = the density of the air,
a = the area of the flat plate in square feet, and
V = the velocity of the air in feet per second.

PROBLEM 17. What is the force of the air blowing at right angles to a sign 6 feet by 10 feet at 30 miles an hour at an elevation of 2600 feet?

SOLUTION. Solve the flat-plate drag formula.

$$F = 1.28 \frac{\rho}{2} aV^2$$

1. $\frac{\rho}{2}$ for 2600 feet = .0011
2. $a = 6 \times 10 = 60$ square feet
3. 30 miles per hour = $1.467 \times 30 = 44$ feet per second
4. $F = 1.28 \times .0011 \times 60 \times 44^2 = 163.6$

The force is about 164 pounds.

EXERCISE 33. With what force does the wind, blowing at 60 miles an hour, strike a billboard 8 feet by 20 feet at an elevation of 1100 feet?

EXERCISE 34. What is the force of a 60-mile wind against the wall of a house 20 feet by 40 feet at an elevation of 2600 feet?

EXERCISE 35. Suppose a parachute were made with a flat plate instead of a curved top. If the supposed flat top of the parachute were round with a radius of 13 feet, what would be the force retarding the descent at 10 feet per second? (Area of a circle = 3.14 × square of the radius.) (Let $\rho = .002$.)

PROBLEM 18. Find the speed at which a 153-pound man would fall in the parachute of Exercise 35.

SOLUTION. $1.28 \frac{\rho}{2} aV^2 = 153$ pounds

1. $\frac{\rho}{2} = .001$
2. $a = 3.14 \times 13^2 = 531$ square feet
3. $1.28 \frac{\rho}{2} aV^2 = 1.28 \times .001 \times 531 \times V^2 = .67968\, V^2$ (or $.68\, V^2$)
4. $.68\, V^2 = 153$
5. $V^2 = 153 \div .68 = 225$
6. $V = \sqrt{225} = 15 \quad (15 \times 15 = 225)$

The 153-pound man would fall at 15 ft. per sec.

EXERCISE 36. Find the speed at which a man weighing 174 pounds would fall in the parachute of Exercise 35. (Solve the equation: $.68\, V^2 = 174$.)

Parasite drag

You have already learned that the fuselage, struts, wheels, and other parts produce drag on an airplane, in addition to the drag on the wing. These parts which produce no lift, when taken together are called the *parasite* of the plane. The drag of these parts is called *parasite drag* ($D_{par.}$). The engine has to supply the thrust necessary to overcome both the wing drag (D_{wing}) and the parasite drag ($D_{par.}$).

Equivalent flat-plate area

Just as we need a coefficient of lift for finding the lift of a wing under varying conditions of air density, wing area, and velocity, we need a coefficient of parasite drag.

Now the parasite drag of a plane varies as the air density and the square of the velocity. Hence, in order to enable us to compute the parasite drag of a given airplane it is customary to tell what flat-plate area would give the same drag as the plane under similar conditions. This area is called the *equivalent flat-plate area of the parasite.*

If the letter a in the formula $F = 1.28 \frac{\rho}{2} aV^2$ is the equivalent flat-plate area of the parasite of a plane, then F = the parasite drag. The parasite drag may be found, therefore, by means of this formula:

$D_{par.} = 1.28 \frac{\rho}{2} aV^2$ (Formula for parasite drag)

in which —

$D_{par.}$ = the parasite drag,
ρ = the density of the air,
a = the equivalent flat-plate area of the parasite, and
V = the velocity of the plane, in feet per second.

PROBLEM 19. The equivalent flat-plate area of a Lockheed monoplane is 3.5 square feet. What is the parasite drag at 100 miles an hour, where $\rho = .002$?

SOLUTION. Solve the formula for parasite drag:

$$D_{par.} = 1.28 \frac{\rho}{2} aV^2$$

1. $\rho = .002$, $\frac{\rho}{2} = .001$
2. $a = 3.5$.
3. $V = 1.467 \times 100 = 146.7$
4. $V^2 = 21521$
5. $D_{par.} = 1.28 \times .001 \times 3.5 \times 21521 = 96.4$ pounds

EXERCISE 37. What is the parasite drag on a plane flying at 136 miles an hour (see Table 3, page 169) where $\rho = .002$, if the parasite has an equivalent flat-plate area of 5 square feet?

Finding total drag

Obviously total drag equals wing drag plus parasite drag. Thus:

$$\text{Total drag} = \text{Wing drag} + \text{Parasite drag, or}$$
$$D_{plane} = D_{wing} + D_{par.}$$

PROBLEM 20. What is the total drag on a plane with Clark Y wing of 170 square feet area, flying at 5800 feet, at 82 miles an hour, at 1° angle of attack, if the flat-plate equivalent of the parasite is 1.5 square feet?

SOLUTION. Find D_{wing}, then $D_{par.}$ and add.

$$D_{wing} = C_D \tfrac{\rho}{2} S V^2$$

1. C_D (Clark Y, 1°) = .021
2. $\frac{\rho}{2} = .001$
3. $S = 170$
4. $V^2 = 14400$
5. $D_{wing} = .021 \times .001 \times 170 \times 14400 = 51.4$ pounds

$$D_{par.} = 1.28 \tfrac{\rho}{2} a V^2$$

6. $a = 1.5$
7. $D_{par.} = 1.28 \times .001 \times 1.5 \times 14400 = 27.6$ pounds
8. $D_{plane} = 51.4 + 27.6 = 79$ pounds

The total drag of the plane is 79 pounds.

Thrust equals drag

The total propeller thrust needed to fly a plane equals the total drag, and hence, of course, thrust equals wing drag plus parasite drag.

The thrust needed to propel the plane of Problem 20 is 79 pounds.

EXERCISE 38. What is the thrust needed to propel a plane with Göttingen wing of 160 square feet area, flying at 5800 feet, at 95 miles an hour, at 2° angle of attack, if the flat-plate equivalent of the parasite is 1.6 square feet?

Relation of parasite drag to wing drag

The parasite drag is sometimes greater than the wing drag and sometimes less. The ratio of the two drags at cruising speed depends in part on the type of plane — whether it has a large or a small wing for its size and weight, in part on the number of struts, wires, and such, and in part on the streamlining — whether the landing wheels are retracted, and in part on the smoothness of surface — whether there are projecting rivet heads, and the like.

If the plane is flying at a high angle of attack, the wing drag is greatly increased. The drag of the fuselage is increased some, but the drag of the landing gear, struts, etc., is not increased; hence the parasite drag is increased less than the wing drag. Therefore the ratio of parasite drag to wing drag is less at high angles of attack.

Wing-tip vortices

Since the pressure of air is reduced on the upper surface of a wing and increased (as a rule) on the lower surface, the air tends to flow away from the fuselage under the wing tip and toward the fuselage over the wing tip. This creates a swirl behind each wing tip, as shown in Figure 117. This swirl is called a *wing-tip vortex*. A certain amount of lift is lost because of the wing-tip vortices (vor′ti-sees; plural of *vortex*).

The narrower the wing, the less the loss of lift through the vortices.

You can see that in order to make a wing of 200 square feet area with the least possible loss of lift through wing-tip vortices, it is necessary to make the wing as narrow as possible. But the narrower the wing is made, the longer it must be; that is, if it is made with a 6-foot chord, the span could be $33\frac{1}{3}$ feet. If made with a 5-foot chord, the span must be 40 feet.

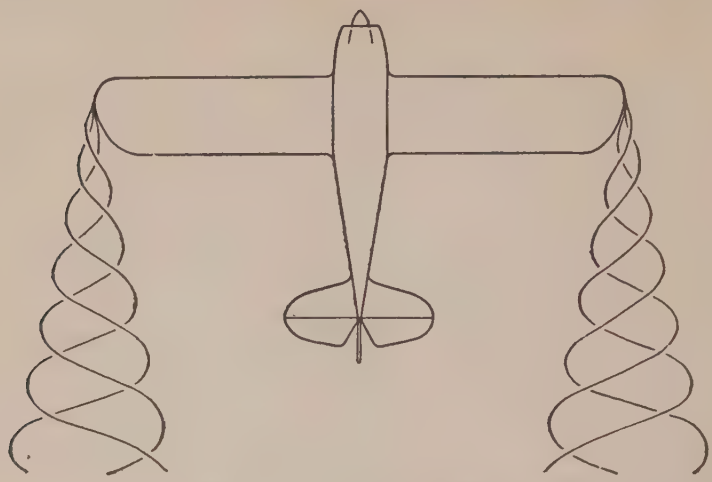


FIG. 117. Wing-tip vortices.

Aspect ratio

The ratio of the *span* of a wing (length from tip to tip) to its *mean chord* (average chord) is called its *aspect ratio.* To avoid loss of lift through wing-tip vortices, it is desirable to make the aspect ratio as great as possible.

Obviously structural considerations place a limit on the possible aspect ratio. That is, we cannot narrow a wing and lengthen it indefinitely because as we do so we reduce its strength.

Gliders can be built with an aspect ratio as high as 20 (the wing is 20 times as long as it is wide); but the aspect ratios of powered airplanes are usually between 6 and 8.

It has been customary to report coefficients of lift and drag, as of a wing with an aspect ratio of 6. Hence if the aspect ratio is 8 we know the coefficient of lift will be a little greater than reported for the aspect ratio of 6. The increase is ordinarily about 6 per cent. However, the coefficient of drag may be reduced as much as 15% by changing the aspect ratio from 6 to 8.

Questions

1. What is meant by lift and drag with reference to a wing?
2. What is a wind tunnel, and how is it used?
3. In what sense is a wind tunnel a Venturi tube?
4. How is the lift of a wing related to its area?
5. How is the lift of a wing related to the velocity of the air flowing past it?
6. What is meant by scale effect?
7. What is the relation between the drag of a wing and its area?
8. What is the relation between the drag of a wing and the velocity of the air?
9. If the velocity of a wing through the air is doubled, is the drag doubled, or more than doubled, or less than doubled?
10. What is the relation between lift and air density?
11. What is meant by unit velocity?
12. What is the relation between density of the air and altitude?
13. At about what altitude is the air one half as dense as at the earth's surface?
14. What is meant by air of unit density?
15. What is mass?
16. What is a slug?
17. How does lift vary with angle of attack?
18. How does drag vary with angle of attack?
19. What is meant by the coefficient of lift?
20. What is meant by the coefficient of drag?
21. What is meant by the expression $\rho = .002378$?
22. What is the formula for the coefficient of lift?
23. What is the formula for the coefficient of drag?
24. Which is greater for a given angle of attack, the coefficient of lift or the coefficient of drag?
25. How is the total lift of a wing found when you know the coefficient of lift?
26. What is meant by thrust?
27. What is the relation between thrust and drag?
28. How do you convert miles per hour into feet per second?

29. What is meant by parasite drag?
30. What is the formula for the force of air against a flat plate in terms of density of the air, area of the flat plate, and velocity of the air?
31. How is the force of the wind against a flat plate related to the velocity of the wind?
32. What is meant by "equivalent flat plate area"?
33. What is the relation between total drag, wing drag, and parasite drag?
34. What is meant by a wing-tip vortex?
35. Explain the direction of rotation of wing-tip vortices.
36. What is meant by aspect ratio?
37. About what is the aspect ratio of an ordinary airplane?

FIG. 118. Engine-assembly line at the plant of the Wright Aeronautical Corporation in Paterson, New Jersey.

15

SPEED AND POWER

IN THE preceding chapter you learned among other things —

(1) how to find the total lift and drag on a full-size airplane wing when given the lift and drag on a small model wing, taking into account (*a*) change of wing area, (*b*) change of velocity, and (*c*) change of air density;

(2) how to find the lift and drag of a wing of given area, flying at a given angle of attack, in air of given density, when you know the type of wing and its lift and drag characteristics;

(3) how to find the force of moving air acting on a flat plate at right angles to the motion of the air;

(4) how to find the parasite drag of a plane when you know the equivalent flat-plate area of the parasite and the air density and velocity; and

(5) how to find the thrust needed to propel a plane at a given angle of attack to overcome wing drag and parasite drag.

You should realize that the problems you are studying now are among those an airplane designer often needs to solve.

Among other things an airplane designer must know are:

(1) What velocity is necessary to give a plane the lift necessary to sustain its weight.

(2) What horsepower is necessary to give a plane the velocity necessary to get the lift necessary to sustain its weight.

(3) What is the relation between necessary velocity and angle of attack.

(4) What is the relation between necessary power and angle of attack.

(5) What is the effect of change of altitude upon required velocity and required power.

(6) What is the effect of change of wing area on required velocity and required power.

(7) What is the effect of change of weight on required velocity and required power.

(8) What is the effect of changing both the weight and the wing area of an airplane on the required velocity and required power.

This chapter and the next one are designed to help you understand these relations and effects.

VELOCITY

Finding the required velocity

We saw in the preceding chapter (Fig. 116) how lift and drag increase with velocity at a given angle of attack. It is not necessary to draw a lift graph as in Figure 116 to find the velocity necessary to create enough lift to sustain the weight of the plane at a given angle of attack.

To find the velocity necessary to create lift sufficient to sustain a plane, we have merely to let L in the lift formula equal the weight of the plane and solve for V, as illustrated in Problem 1.

PROBLEM 1. Find the velocity and air speed (A) necessary to sustain a 1500-pound plane of 200 square feet wing area (Clark Y type) at 1° angle of attack at 5800 feet altitude.

SOLUTION. Solve the formula $L = C_L \frac{\rho}{2} SV^2$ for V when $L = 1500$.

1. $C_L = .43$
2. $\frac{\rho}{2} = .001$
3. $S = 200$

Substituting these values in the formula, we have —

4. $1500 = .43 \times .001 \times 200 \times V^2$

5. $V^2 = \dfrac{1500}{.43 \times .001 \times 200} = \dfrac{1500}{.086} = 17442$

6. $V = \sqrt{17{,}442} = 132$ (feet per second)

7. $A = .682 \times 132 = 90$ (miles per hour)

A velocity of 132 feet per second or 90 miles an hour is needed to fly at 1° angle of attack under the conditions given.[1]

The result, 132 feet per second, is the same as we found in Figure 114 of the preceding chapter, by drawing a graph of velocities and finding the velocity necessary to lift 1500 pounds.

Formula for required velocity

It is convenient to have a formula arranged for finding the velocity necessary to fly at a given angle of attack, with a given wing area, in air of a given density, and creating enough lift to sustain the weight of the plane.

To find such velocity we solve the lift formula exactly as in Problem 1 but merely by using the letters. Thus, if the lift must equal the weight,

$$L = C_L \tfrac{\rho}{2} S V^2 = W \qquad \text{Hence } V^2 = \frac{W}{C_L \frac{\rho}{2} S}$$

So $$V = \sqrt{\frac{W}{C_L \frac{\rho}{2} S}}$$ (Formula for finding the velocity necessary to sustain the weight of the plane under given conditions)

This formula means that to find the velocity of a plane necessary to sustain a given total weight at a given angle of attack when we know the wing area, we —

(1) find $C_L \times \frac{\rho}{2} \times S$,

(2) divide the weight W by this product, and

(3) find the square root of the quotient.

[1] Actually, a plane of this weight and wing area can take off at much less than 90 miles an hour air speed by taking off at a higher angle of attack, as you will see later.

We would read this formula as follows: Necessary velocity V = the square root of the quotient obtained by dividing W by the product of C_L, $\frac{\rho}{2}$, and S.

By this formula our solution to Problem 1 is

$$V = \sqrt{\frac{1500}{.43 \times .001 \times 200}}$$
$$= \sqrt{17{,}442}$$
$$= 132 \text{ feet per second}$$

Finding square roots

There are various methods of finding the square root of a number. There is a complicated method which is difficult to learn and remember. Another way is to guess at the square root of the number and check by multiplying.

Thus, to find the square root of 17,442 you would think

(1) $100 \times 100 = 10{,}000$; so it is more than 100
$200 \times 200 = 40{,}000$; so it is less than 200
$130 \times 130 = 16{,}900$; so it is more than 130
$131 \times 131 = 17{,}161$; so it is more than 131
$132 \times 132 = 17{,}424$; so it is about 132

Finding square root by the table

A good method of finding the square root of a number is by means of the Table of Squares and Square Roots (page 643). To use the table for finding the square root of a number of over three figures, you proceed as follows:

To find the square root of 54,321 —

(1) mark off *two* figures at the right (543 | 21),

(2) look up the square root of 543 in the table ($\sqrt{543}$ = 23.302),

(3) move the decimal point *one* place to the right (233.02);

(4) 233.02 is the square root of 54,300, therefore $\sqrt{54{,}321}$ = a little over 233.

To find the square root of 5678, the steps are as follows:
(1) 5678 = about 5700,
(2) mark off two figures at right, as before (57 | 00),
(3) $\sqrt{57} = 7.550$,
(4) $\sqrt{5700} = 75.5$
(5) $\sqrt{5678}$ = a little less than 75.5.

A second method of using the table is as follows:

To find the square root of 54,321, look in the column of squares. We find that —

$$233^2 = 54{,}289; \text{ hence } \sqrt{54{,}289} = 233$$
$$234^2 = 54{,}756; \text{ hence } \sqrt{54{,}756} = 234$$
$$\text{Therefore } \sqrt{54{,}321} = 233^+$$

Exercise 1. Find the velocity necessary to lift a plane weighing 1600 pounds, having a Clark Y wing of 200 square feet area, at 1° angle of attack, at 4200 feet altitude.

The popular light planes

There are several popular light planes used by private pilots and for training purposes. These planes weigh about 1150 pounds and have a wing area of about 170 square feet and a parasite of about 4.3 square feet. Let us investigate the relation of required velocity to angle of attack for a plane of these specifications.

Problem 2. What are the velocity and air speed necessary to fly a 1150-pound plane, of Clark Y wing of 170 square feet area, at an altitude of 5800 feet ($\rho = .002$), at $-2°$, 0°, 4°, 6°, 8°, and 18° angle of attack?

Solution. Solve the formulas

$$V^2 = \frac{W}{C_L \frac{\rho}{2} S} \text{ and } A = .682\,V$$

1. For $-2°$, $C_L = .216$
2. $\frac{\rho}{2} = .001$
3. $S = 170$

4. $V^2 = \dfrac{1150}{.216 \times .001 \times 170} = \dfrac{1150}{.0367} = 31{,}335$

5. $V = \sqrt{31{,}335} = 177$ feet per second

6. Air speed $= .682 \times 177 = 121$ miles per hour

The computation for the various angles of attack is shown in Table 7.

TABLE 7

SHOWING THE COMPUTATION OF VELOCITIES AND AIR SPEEDS FOR PROBLEM 2

ANGLE OF ATTACK	C_L	DENOMINATOR $C_L \times .001 \times 170$	V^2 1150 ÷ DENOM.	V	AIR SPEED
− 2	.216	.0367	31,335	177	121
0	.358	.0609	18,883	137	93
2	.500	.0850	13,529	116	79
4	.644	.1094	10,512	103	70
6	.789	.1341	8,576	92.6	63
8	.937	.1593	7,219	85.0	58
18	1.540	.2618	4,393	66.3	45

Figure 119 shows the air speeds necessary for the light plane at the various angles of attack, as found in Table 7.

EXERCISE 2. Find the velocity and air speed necessary for the light plane of Problem 2 at 1°, 3°, 5°, and 7° angle of attack.

Slow speed with high angle of attack

Note that for the low angles of attack a high air speed is required in order to get the necessary lift; but that as the angle of attack increases, the necessary air speed diminishes until at 18° the least velocity is required. This shows why it is necessary to pull up the nose of the plane while preparing to land. It is to enable the plane to fly as slowly as possible.

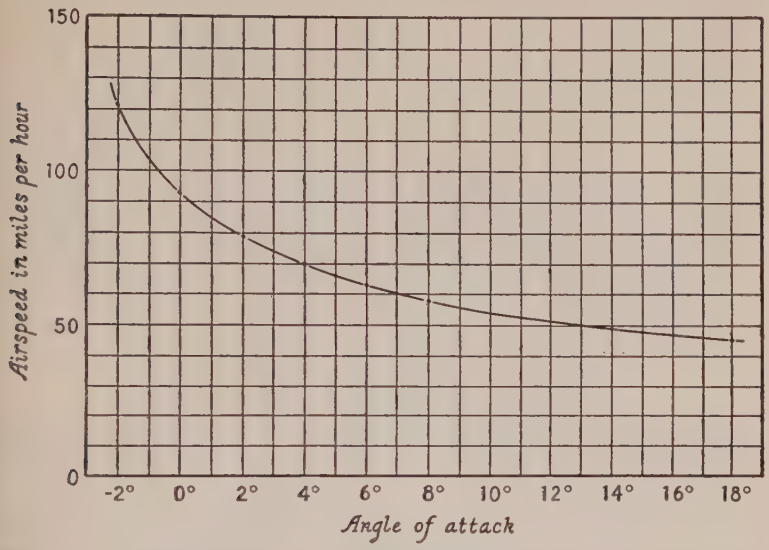


FIG. 119. Graph showing the air speed necessary to sustain the plane of Problem 2, page 191, at various angles of attack.

Minimum flying speed

If we examine the curve of lift in Figure 112 of Chapter 14, we see that in the case of a Clark Y airfoil the lift increases with increase in angle of attack up to about 18° angle of attack. Then the lift ceases to increase and after 20° falls off.

Obviously 20° is about the burbling angle, or stalling angle, of this airfoil. Let us assume, therefore, that 18° is about the maximum safe angle of attack at which a plane with Clark Y wing can fly.

We can use our velocity formula to find the minimum flying speed of a plane of given total weight and wing area, as shown in Problem 3. For this purpose we might write the velocity formula in this way:

$$\text{Min. } V = \sqrt{\frac{W}{\text{Max. } C_L \frac{\rho}{2} S}}$$

This means,

$$\text{Slowest landing speed} = \sqrt{\frac{\text{Weight}}{\begin{pmatrix}\text{Maximum}\\ \text{coef. of lift}\end{pmatrix} \times \frac{\rho}{2} \times \begin{pmatrix}\text{wing}\\ \text{area}\end{pmatrix}}}$$

PROBLEM 3. What is the minimum flying speed (in miles per hour) of a light plane of 1200 pounds' total weight, with Clark Y wing of 170 square feet area, landing on an airport of 1100 feet elevation, assuming the maximum safe angle of attack to be 18°?

SOLUTION. Solve the formulas,

$$\text{Min. } V = \sqrt{\frac{W}{\text{Max. } C_L \frac{\rho}{2} S}} \text{ and } A = .682\, V$$

1. C_L at 18° = 1.54
2. $\frac{\rho}{2}$ at 1100 feet = .00115
3. $S = 170$
4. $C_L \times \frac{\rho}{2} \times S = 1.54 \times .00115 \times 170 = .301$
5. $\frac{1200}{.301} = 3987$
6. $\sqrt{3987}$ = about 63.1
7. Min. V = 63.1 (feet per second)
8. Min. $A = .682 \times 63.1 = 43$ (miles per hour)

The minimum flying speed of this plane is 43 miles an hour. The plane could land at this speed at this airport.

EXERCISE 3. What would be the minimum flying speed of the plane in Problem 3, if the weight were 1300 pounds and the wing area 180 square feet?

EXERCISE 4. A DC–3 fully loaded weighs 24,400 pounds. What would be the minimum flying speed of a plane of that weight having a Clark Y wing of 1440 square feet, flying at 1100 feet, at 18° maximum safe angle of attack (without flaps)?

THRUST

You have already learned that thrust = drag, and that there are two kinds of drag, wing drag (D_{wing}) and parasite

drag ($D_{par.}$). Perhaps you can remember the shorter symbols D_w and D_p for wing drag and parasite drag.

It is often convenient to divide thrust into two parts: (1) the thrust necessary to overcome wing drag (this we may call thrust for the wing — T_{wing}), and (2) the thrust necessary to overcome parasite (this we may call thrust for the parasite — $T_{par.}$).

Since thrust = drag, the thrust for the wing equals the wing drag, and the thrust for the parasite equals the parasite drag. Hence,

$$T_{wing} = C_D \tfrac{\rho}{2} SV^2$$
$$T_{par.} = 1.28 \tfrac{\rho}{2} aV^2 \text{ and}$$

the total thrust (T_{total}) equals the thrust for the wing plus the thrust for the parasite; that is,

$$T_{total} = T_{wing} + T_{par.}$$

PROBLEM 4. Find the thrust necessary to maintain a velocity of 90 miles an hour in a plane of Clark Y wing of 200 square feet wing area, at 1° angle of attack, at 5800 feet altitude, if a (the equivalent flat-plate area of the parasite) is 3.6 square feet.

SOLUTION. Find T_{wing} and $T_{par.}$ by the formulas

$$T_{wing} = C_D \tfrac{\rho}{2} SV^2 \text{ and } T_{par.} = 1.28 \tfrac{\rho}{2} aV^2$$

1. $C_D = .021$
2. $\frac{\rho}{2} = .001$
3. $S = 200$
4. 90 miles per hour = 132 feet per second
5. $V^2 = 132^2 = 17{,}424$
6. $T_{wing} = .021 \times .001 \times 200 \times 17{,}424$
   $= 73$ pounds
7. $T_{par.} = 1.28 \times .001 \times 3.6 \times 17{,}424$
   $= 80$ pounds
8. Total = 73 + 80 = 153 pounds

The necessary thrust is 153 pounds.

EXERCISE 5. Find the thrust necessary for a plane of Clark Y wing of 250 square feet area, to maintain a velocity of 82 miles an hour (Table 3, Chapter 14) at 7500 feet altitude, at 1° angle of attack. (a = 8.4 square feet)

PROBLEM 5. Find the velocity and thrust necessary to lift a plane of 1600 pounds with Göttingen 398 wing of 300 square feet area, at 2600 feet altitude, at 1° angle of attack. (a = 7 square feet)

SOLUTION. First find the required velocity, then the thrust.

1. $V = \sqrt{\dfrac{W}{C_L \frac{\rho}{2} S}}$
2. $C_L = .51$
3. $\frac{\rho}{2} = .0011$
4. $S = 300$
5. Denominator $= .51 \times .0011 \times 300 = .1683$
6. $W = 1600$
7. $1600 \div .1683 = 9507$
8. $V = \sqrt{9507} = 97.5$ feet per second required velocity
9. $.682 \times 97.5 = 66.5$ miles per hour required air speed
10. Thrust $= T_{wing} + T_{par.}$
11. $T_{wing} = C_D \frac{\rho}{2} S V^2$
12. $C_D = .025$
13. $V^2 = 9507$
14. $T_{wing} = .025 \times .0011 \times 300 \times 9507 = 78.4$ pounds
15. $T_{par.} = 1.28 \frac{\rho}{2} a V^2$
16. $a = 7$
17. $T_{par.} = 1.28 \times .0011 \times 7 \times 9507 = 93.7$ pounds
18. Thrust $= 78.4 + 93.7 = 172.1$ pounds

The required thrust is about 172 pounds.

EXERCISE 6. Find the thrust needed to propel a plane with Göttingen 398 wing of 180 square feet area, at 1° angle of attack, at 1100 feet altitude, the plane when loaded weighing 1350 pounds. (a = 5 square feet) (First find the required velocity as in Problem 5.)

Relation of thrust to weight

We know that

$$\text{Lift} = C_L \tfrac{\rho}{2} S V^2$$

and

$$\text{Drag} = C_D \tfrac{\rho}{2} S V^2$$

And when the plane is in straight and level flight,

$$\text{Weight} = \text{Lift}$$

and

$$\text{Thrust} = \text{Drag}$$

Hence $$\frac{\text{Thrust}}{\text{Weight}} = \frac{\text{Drag}}{\text{Lift}} = \frac{C_D \frac{\rho}{2} S V^2}{C_L \frac{\rho}{2} S V^2} = \frac{C_D}{C_L}$$

Therefore we can find the thrust for the wing from the weight by the formula

$$\text{Thrust} = \frac{\text{Drag}}{\text{Lift}} \times \text{Weight}$$

or

$$\text{Thrust} = \frac{C_D}{C_L} \times \text{Weight}$$

We use the symbol D/L for $\frac{\text{Drag}}{\text{Lift}}$, so

$$\text{Thrust for the wing} = D/L \times \text{Weight}$$

The formulas above show that the thrust in straight and level flight at a given angle of attack can be found thus: multiply the weight by the quotient obtained by dividing the coefficient of drag by the coefficient of lift for the angle of attack. Thus, at a given angle of attack, if C_D is $\frac{1}{10}$ of C_L, Thrust = $\frac{1}{10}$ of Weight.

Figure 120 shows the values of the ratio of lift to drag (C_L/C_D) and the ratio of drag to lift (C_D/C_L) for the Clark Y wing at various angles of attack.

The figure shows that C_L/C_D (Lift ÷ Drag) for the Clark Y wing is 7.4 at − 4° (see left-hand scale), 12.8 at − 3°, 17.2 at − 2°, etc. The values of C_D/C_L (Drag ÷ Lift) are: .136 at − 4°, .077 at − 3°, .058 at − 2°, etc.

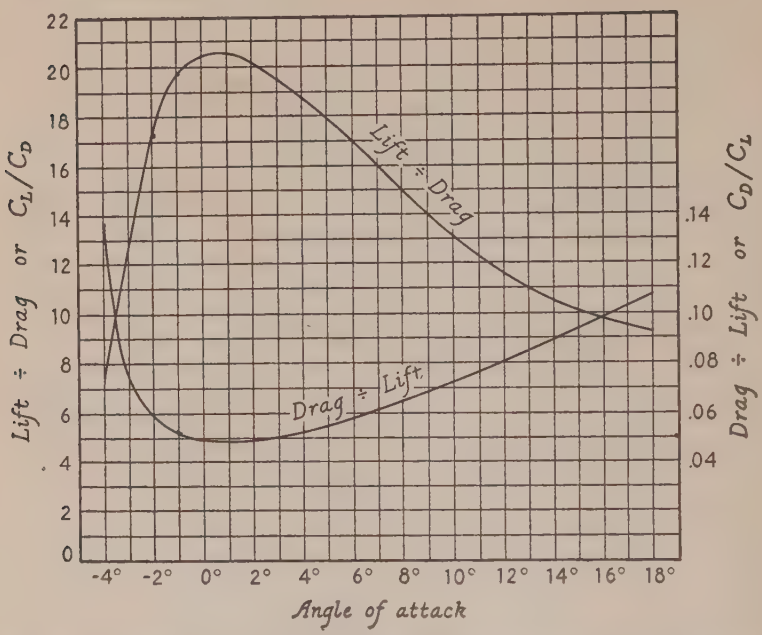


FIG. 120. Graph of the L/D and D/L ratios of the Clark Y wing at various angles of attack.

The ratio C_L/C_D is sometimes written L/D. The ratio C_D/C_L is sometimes written D/L (the ratio of the lift and drag of a wing is the same as the ratio of the coefficients).

EXERCISE 7. Find from Figure 120 the values of L/D and D/L for angles of attack: $-2°$, $-1°$, $0°$, $1°$, $2°$, $3°$, $4°$, $5°$, and $6°$. Write the values in a table.

PROBLEM 6. What thrust is needed for propelling the Clark Y wing of a 2500-pound plane in straight and level flight at 2° angle of attack?

SOLUTION. Solve the thrust formula

$$\text{Thrust for a wing} = C_D/C_L \times \text{Weight of plane}$$

1. C_D/C_L for $2° = .049$ (Fig. 120)
2. Thrust $= .049 \times 2500 = 122.5$ pounds

The thrust for the wing is 122.5 pounds.

EXERCISE 8. What is the thrust needed for the Clark Y wing of a 2000-pound plane at $-2°$, $-1°$, $0°$, $1°$, $2°$, $3°$, and $4°$ angle of attack? For which angle was the thrust least?

POWER

Power is the ability to do work at a given rate. In Problem 4 we found the thrust of the propeller to be 153 pounds to propel the plane at 90 miles an hour. It takes only a very little power to exert a thrust of 153 pounds in pushing an object only one foot per second. You have more power than that in your muscles. But to exert that amount of thrust at 90 miles an hour — that is different.

Foot-pounds

If a force or thrust of one pound acts over a distance of one foot, we say the force does one unit of *work*. We call the unit a *foot-pound*.

If a force or thrust of one pound acts through a distance at the rate of one foot per second, we say the force does work at the rate of *one foot-pound per second*.

If a force or thrust of 113 pounds acts through a distance at the rate of one foot per second, we say the force does work at the rate of 113 foot-pounds per second.

If a propeller thrust of 113 pounds pulls a plane through the air at a velocity of 100 feet a second, we say that the thrust does work at the rate of 11,300 foot-pounds per second.

The number of foot-pounds of work per second which a thrust does is found, therefore, by multiplying the number of pounds of thrust by the number of feet per second through which the thrust acts.

Briefly, we may say that the rate of work in foot-pounds per second equals the thrust times the velocity. Or

$$\text{Rate of work} = TV$$

Horsepower

When the rate of work is 550 foot-pounds per second, we say that one horsepower is being generated.

To find the number of horsepower being generated in a given case, we first find the rate of work in foot-pounds per second and then divide by 550. That is,

$$\text{Horsepower} = \frac{\text{Rate of work}}{550},$$

or

$$H.P. = \frac{\text{Thrust} \times \text{Velocity}}{550},$$

or

$$H.P. = \frac{TV}{550} \qquad \text{(Power formula)}$$

Remember that V is in feet per second.

PROBLEM 7. What horsepower is being exerted by the propeller of the plane if the thrust is 91 pounds and the velocity is 90 miles an hour?

SOLUTION. Solve the power formula.

$$H.P. = \frac{TV}{550}$$

1. $V = 1.467 \times 90 = 132$ feet per second
2. $H.P. = \dfrac{91 \times 132}{550} = 21.8$

The propeller is delivering about 22 horsepower.

EXERCISE 9. What horsepower is needed to fly a plane with thrust of 250 pounds at 150 miles an hour?

PROBLEM 8. What horsepower is being required of the propeller of a plane which must exert a thrust of 113 pounds at 90 miles an hour?

SOLUTION. Solve the formula $H.P. = \dfrac{TV}{550}$.

1. $T = 113$
2. $V = 1.467 \times 90 = 132$ feet per second

3. $H.P. = \frac{113 \times 132}{550} = \frac{14{,}916}{550} = 27$

Twenty-seven horsepower are required to propel the plane in straight and level flight under the conditions. No doubt the plane has available more power than this, which can be used for climbing and turning, as you will see later.

EXERCISE 10. What horsepower is needed for a plane requiring 120 pounds of thrust to fly at 95 miles an hour?

Horsepower required for a wing

It is frequently desirable to find separately the horsepower necessary for a wing only, taking care of parasite drag in a separate formula.

If it is desired to find the horsepower for flying a wing of given area at a given angle of attack, in air of given density, at a given velocity, we can insert the value of wing drag $(C_D \frac{\rho}{2} SV^2)$ for thrust in the horsepower formula $H.P. = \frac{TV}{550}$ and we have

$$H.P. = \frac{(C_D \frac{\rho}{2} SV^2)V}{550}$$

or $$H.P. = \frac{C_D \frac{\rho}{2} SV^3}{550}$$ (Formula for horsepower required for a wing)

PROBLEM 9. What power is needed for a Lockheed Electra wing of 458 square feet area to fly at 4° angle of attack at 1100 feet altitude, at 191 miles an hour, if the airfoil is the Clark Y?

SOLUTION. Solve the formula for required horsepower.

$$H.P. = \frac{(C_D \frac{\rho}{2} SV^2)V}{550}$$

1. C_D at 4° for Clark $Y = .033$

2. $\frac{\rho}{2} = \frac{.0023}{2} = .00115$

3. $S = 458$
4. $V = 1.467 \times 191 = 280$ feet per second
5. $V^2 = 280^2 = 78{,}400$
6. $H.P. = \dfrac{.033 \times .00115 \times 458 \times 78{,}400 \times 280}{550} = \dfrac{38{,}155}{550} = 693.7$

The wing will need about 694 horsepower.

EXERCISE 11. A Boeing bomber has a wing area of 954 square feet. If the plane had Clark Y wing, what horsepower would be needed to propel the wing at 0° angle of attack, at 177 miles an hour, at 5800 feet altitude?

EXERCISE 12. A plane has a Göttingen 398 wing of 183 square feet. What horsepower would be needed to propel this wing at a speed of 136 miles an hour, at 5800 feet altitude, at − 2° angle of attack?

EXERCISE 13. A Detroit Lockheed YP–24 has a Clark Y wing of 292.0 square feet area. What horsepower would be needed to propel this wing at 214 miles an hour, at 9200 feet altitude, at − 1° angle of attack?

Finding the horsepower for a wing from the weight and velocity

If we know the weight of the plane and the velocity necessary to sustain the weight at a given angle of attack, we can find the horsepower required to fly the wing under the given conditions by means of the formula,

$$H.P. = \frac{(D/L \times W)V}{550} \qquad \text{(Formula for horsepower)}$$

You will see that this formula is merely the formula $H.P. = \dfrac{TV}{550}$ with the equivalent of thrust $(D/L \times W)$ substituted for T in the formula.

PROBLEM 10. What horsepower is required for the Clark Y wing of a plane weighing 1850 pounds, flying at 109 miles an hour, at 2° angle of attack?

SOLUTION. Solve the formula

$$H.P. = \frac{(D/L \times W)V}{550}$$

1. For 2°, D/L (that is, C_D/C_L) = .05 (from Figure 120)
2. $W = 1850$
3. $V = 1.467 \times 109 = 160$ feet per second
4. $H.P. = \frac{.05 \times 1850 \times 160}{550} = \frac{14{,}800}{550} = 26.9$

The wing would require about 27 $H.P.$ to fly under the given conditions.

EXERCISE 14. What horsepower is required for the Clark Y wing of a 2000-pound plane flying at 123 miles an hour, at 1° angle of attack? ($D/L = .048$.)

Power needed for parasite drag

The power of the propeller needed to overcome parasite drag can be found, of course, by the same formula $H.P. = \frac{\text{Thrust} \times \text{Velocity}}{550}$. That is, the thrust necessary to overcome the parasite drag equals that drag; hence the horsepower ($H.P._{par.}$) necessary to overcome that drag equals Parasite drag × Velocity ÷ 550. Or —

$$H.P._{par.} = \frac{(1.28\,\frac{\rho}{2}aV^2)V}{550}$$

or $$H.P._{par.} = \frac{1.28\,\frac{\rho}{2}aV^3}{550}$$ (Formula for horsepower for parasite drag)

in which —

$H.P._{par.}$ is the horsepower necessary to overcome parasite drag,

ρ is the density, in slugs per cubic foot,

a is the equivalent flat-plate area of the parasite, and

V is the velocity of the plane, in feet per second.

PROBLEM 11. What horsepower is required for the para-

site drag of a plane whose parasite has an equivalent flat-plate area of 3.5 square feet, flying at 100 miles an hour, where $\rho = .002$?

SOLUTION. Solve the formula

$$H.P. = \frac{(1.28\,\frac{\rho}{2}aV^2)V}{550}$$

1. $V = 1.467 \times 100 = 146.7$ feet per second. $V^2 = 21{,}521$
2. $\frac{\rho}{2} = .001$
3. $a = 3.5$
4. $H.P. = 1.28 \times .001 \times 3.5 \times 21{,}521 \times 146.7 \div 550 = 25.7$

The parasite drag of the plane to be overcome requires 25.7 horsepower under the given conditions.

EXERCISE 15. What horsepower is required to overcome the parasite drag as in Problem 11 if the air speed is 136 miles an hour and the equivalent flat-plate area is 4 square feet?

Horsepower for a plane

Since we may think of a plane as made up of the wing and the parasite, a plane requires horsepower for both the wing and the parasite. Hence

$$H.P._{plane} = H.P._{wing} + H.P._{par.}$$

PROBLEM 12. A plane of 1200 pounds has a Clark Y wing of 170 square feet area and a parasite with flat-plate equivalent of 3 square feet. What horsepower is required to fly the plane at 5800 feet ($\rho = .002$), at 82 miles an hour, at 2° angle of attack?

SOLUTION. Since we know the weight, we can find the horsepower for the wing by the formula, $H.P._{wing} = \frac{(D/L \times W)V}{550}$.

1. D/L for $2° = .05$
2. $W = 1200$
3. $V = 1.467 \times 82 = 120$ feet per second
4. $H.P._{wing} = \frac{.05 \times 1200 \times 120}{550} = 13.1$

To find the horsepower for the parasite, solve the formula, $H.P._{par.} = \frac{1.28 \frac{\rho}{2} aV^3}{550}$.

5. $\frac{\rho}{2} = .001$
6. $a = 3$
7. $V^3 = 1{,}728{,}000$
8. $H.P._{par.} = 1.28 \times .001 \times 3 \times 1{,}728{,}000 \div 550$
   $= 6635.5 \div 550 = 12.0$
9. $H.P._{plane} = 13.1 + 12.0 = 25.1$

The plane requires about 25 *H.P.* for straight and level flight under the conditions.

EXERCISE 16. A plane weighing 2580 pounds has a Clark Y wing of 150 square feet and a parasite with an equivalent flat-plate area of 4 square feet. What horsepower is necessary to fly the plane at 5800 feet (where $\rho = .002$) at cruising speed of 200 feet per second, at 1° angle of attack?

Variation of horsepower with angle of attack

Let us now find the horsepower needed at a series of angles of attack, and note how the horsepower varies with increase in angle of attack. Let us consider the same light plane as in Problem 2.

PROBLEM 13. What horsepower is needed for the plane of Problem 2 to fly at − 2°, 0°, 2°, 4°, 6°, 8°, and 18° angle of attack at 5800 feet? (W = 1150 pounds; S = 170 square feet; wing = Clark Y; for velocities see Table 7, page 192. Assume the flat-plate equivalent of the parasite to be 4.34 square feet.)

SOLUTION. Since we know the weight and corresponding velocities of the plane, let us use the formula,

$$H.P._{wing} = \frac{(D/L \times W)V}{550}$$

to find the horsepower for the wing. Let us begin with − 2° angle of attack.

1. $D/L = .0582$
2. $W = 1150$
3. $V = 177$
4. $H.P._{wing} = .0582 \times 1150 \times 177 \div 550$
   $= .0582 \times 177 \times 2.09 \quad (1150 \div 550 = 2.09)$
   $= 10.3 \times 2.09 = 21.5$

$$H.P._{par.} = \frac{1.28\,\frac{\rho}{2}aV^3}{550} = \frac{1.28\,\frac{\rho}{2}a}{550} \times V^3$$

5. $\frac{\rho}{2} = .001$
6. $a = 4.34$
7. $V^2 = 31{,}335$, $V = 177$ (from Table 7)
8. $V^3 = 31{,}335 \times 177 = 5{,}546{,}295$
9. $\dfrac{1.28\,\frac{\rho}{2}a}{550} = 1.28 \times .001 \times 4.34 \div 550 = .0000101$
10. $H.P._{par.} = .0000101 \times 5{,}546{,}000 = 56.0$
11. $H.P._{plane} = 21.5 + 56.0 = 77.5$

The computations for the various angles of attack are shown in Table 8.

TABLE 8

COMPUTATIONS OF $H.P._{wing}$ AND $H.P._{par.}$ FOR PROBLEM 12

ANGLE OF ATTACK	D/L	V FROM TABLE 1	$D/L \times V$	$\times 2.09 = H.P._{wing}$	V^3	$\times .0000101 = H.P._{par}$	TOTAL $H.P.$
− 2°	.0582	177	10.3	21.5	5,546,295	56.0	77.5
0°	.0485	137	6.64	13.9	2,586,971	26.1	40.0
2°	.0496	116	5.75	12.0	1,569,364	15.8	27.8
4°	.0536	103	5.52	11.5	1,082,736	10.9	22.4
6°	.0591	92.6	5.47	11.4	794,138	8.0	19.4
8°	.0665	85.0	5.65	11.8	613,615	6.2	18.0
18°	.108	66.3	7.16	15.0	291,256	2.9	17.9

Relation of required horsepower to angle of attack

The values of horsepower required, for the wing, for the parasite, and the total, from Table 8, are plotted in Figure 121 on the following page.

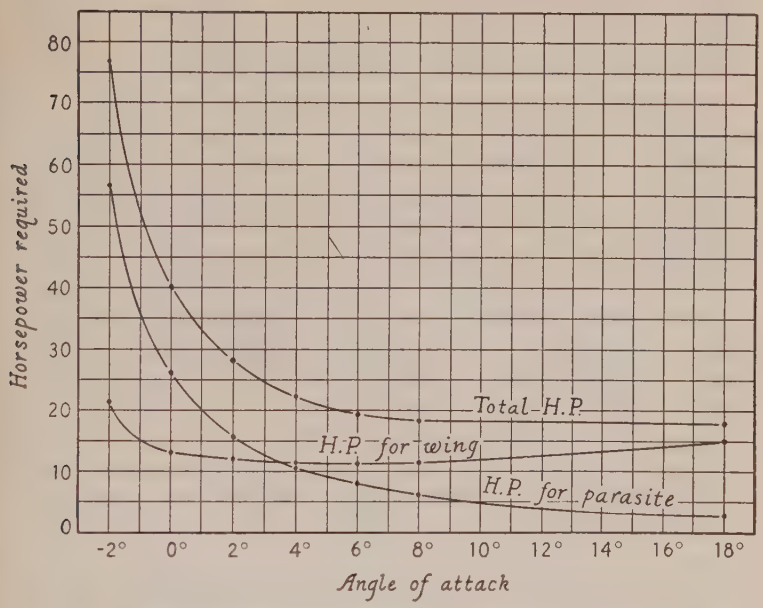


FIG. 121. Graph showing the horsepower needed to fly the light plane of Problems 2 and 11 at various angles of attack.

This figure shows clearly how the amount of horsepower required by this light plane diminishes as we increase the angle of attack, rapidly at first, then slowly.

It shows that for the wing the horsepower decreases with increase of angle of attack up to about 4°, then increases very slightly.

However, the horsepower for the parasite decreases with increase in angle of attack from − 2° to 18°, rapidly at first, then more slowly.

EXERCISE 17. Find the horsepower needed for the wing, for the parasite, and for the whole plane of Problem 13, flying at the necessary velocities at several intermediate angles of attack, 1°, 3°, 5°, and 7°. (You found the necessary velocities in Exercise 2.) Check your results by seeing whether they fit on the curves of Figure 121.

Relation of required horsepower to air speed

It is of interest to see also the way in which required horsepower varies with the air speeds necessary to fly at the various angles of attack of Table 8. Hence the velocities 177, 137, 116, etc., of column 3 were changed to miles per hour, being 121, 93, 79, 70, 63, 58, and 45 respectively, and the values of H.P. from columns 5, 7, and 8 were plotted against these air speeds in Figure 108. The curves drawn through these points show the horsepower needed at various air speeds from 45 to 121 — assuming the plane had horsepower to fly at all these speeds.

Horsepower limitations

The plane is not equipped with an engine of sufficient horsepower to fly at all these air speeds; so let us assume

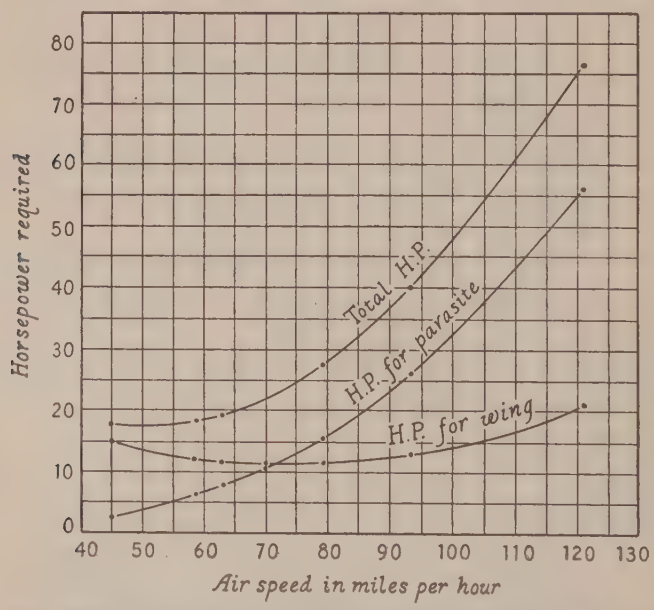


FIG. 122. Graph showing the horsepower needed to fly the light plane of Problems 2 and 11 at various air speeds.

that the engine enables the propeller to deliver 40 horsepower. (An engine may be a 50-horsepower engine but the propeller may deliver only 40 *H.P.*)

We see from Figure 121 that the curve of total horsepower crosses the horizontal line denoting 40 horsepower at a point representing about 0° angle of attack. This shows that the plane can probably fly at 0° angle of attack but not below that angle of attack. (We have seen in Chapter 11 how a wing can have lift at 0° or even less.)

We see from Figure 122 that the curve of total horsepower crosses the 40-horsepower line at a point representing an air speed of 93 miles an hour. If 40 horsepower is the maximum the propeller can deliver, 93 miles an hour is the maximum air speed of the plane.

Questions

1. How do the terms velocity and air speed differ in meaning as used in this text?
2. How would you find the velocity necessary to sustain a plane of given weight and wing area at a given angle of attack and altitude?
3. What is the formula for required velocity?
4. How would you find the square root of 54,321 by means of the table of squares and square roots?
5. What is meant by minimum flying speed?
6. How would you find the miminum flying speed of a plane?
7. How would you find the thrust necessary to propel a given plane?
8. What is meant by power?
9. What is the unit of power?
10. What is the unit of horsepower?
11. What is the formula for horsepower?
12. How do you find the horsepower required to propel a given wing under given conditions?
13. At about what angle of attack may a plane fly with the least required horsepower?

16

AIRPLANE PERFORMANCE

IN Chapter 14 we have seen how the lift and drag of a plane of any given wing area can be found for any given air density and velocity when we know the kind of wing and its lift and drag characteristics.

In Chapter 15 we have seen how we can find the velocity necessary to get the lift to support a plane of any given weight at any angle of attack; also how we can find the horsepower necessary to get the required propeller thrust for both the wing drag and the drag produced by the other parts of the plane, at the velocity necessary to support the plane at the various angles of attack.

It will be of interest now to investigate the effect on airplane performance of taking a plane from sea level to the higher altitudes, and also the effect of changing the weight or the wing area of a plane. These effects are dealt with in this chapter.

EFFECT OF ALTITUDE

We have chosen 5800 feet altitude as the basis of our calculations in various problems for convenience of computation, since the value of $\frac{\rho}{2}$ is .001 for that altitude. But let us see what effect change of altitude has upon the velocity and horsepower necessary for the wing.

For this purpose we have the following formulas for change of velocity and of air speed with density, at the same angle of attack:

$$V_n = \sqrt{\frac{\rho_o}{\rho_n}}\, V_o$$ (Formula for change of velocity with density at the same angle of attack)

$$A_n = \sqrt{\frac{\rho_o}{\rho_n}}\, A_o$$ (Formula for change of air speed with density at the same angle of attack)

in which —

ρ_o = the old density,
ρ_n = the new density,
V_o = the old velocity,
V_n = the new velocity (velocity with the new density),
A_o = the old air speed, and
A_n = the new air speed.

The first formula is read as follows: "V sub n equals V sub o multiplied by the square root of *rho* sub o over *rho* sub n." It means that the new velocity equals the old velocity multiplied by the square root of the quotient found by dividing the old density by the new density.

If $\rho_n = 2 \times \rho_o$, then $V_n = \sqrt{\frac{1}{2}} \times V_o = .707\ V_o$;
if $\rho_n = 3 \times \rho_o$, then $V_n = \sqrt{\frac{1}{3}} \times V_o = .577\ V_o$;
if $\rho_n = 4 \times \rho_o$, then $V_n = \sqrt{\frac{1}{4}} \times V_o = .500\ V_o$;
if $\rho_n = 5 \times \rho_o$, then $V_n = \sqrt{\frac{1}{5}} \times V_o = .447\ V_o$;
and so on.

We see that as ρ_n gets larger V_n gets smaller. We say that V_n varies inversely as the square root of the density, meaning the velocity required to sustain the weight of the plane at the *same angle of attack.*

Problem 1. A plane can fly at 100 miles an hour at 5800 feet altitude. What air speed is required to fly at the same angle of attack at 9200 feet?

Solution. Solve the formula

$$A_n = \sqrt{\frac{\rho_o}{\rho_n}}\, A_o$$

1. $\rho_o = .0020$ (at 5800 feet)
2. $\rho_n = .0018$ (at 9200 feet)
3. $A_o = 100$ miles an hour
4. $\frac{\rho_o}{\rho_n} = \frac{.0020}{.0018} = 1.111$

5. $\sqrt{1.111} = 1.054$ (See the topic immediately following.)
6. $1.054 \times 100 = 105.4$ miles an hour

The required air speed at 9200 feet is 105.4 miles an hour.

The square root of a decimal

To find the square root of a decimal, move the decimal point an even number of places to the right, find the square root, then move the decimal point half as many places to the left.

To find $\sqrt{1.111}$:

(1) Change 1.111 to 111.1.
(2) Find $\sqrt{111.1}$. (It is about 10.54.)
(3) Change 10.54 to 1.054.

$$\sqrt{1.111} = 1.054$$

To find $\sqrt{.909}$:

(1) Change .909 to 90.9.
(2) Find $\sqrt{90.9}$. (It is about 9.53.) ($\sqrt{91} = 9.539$)
(3) Change 9.53 to .953.

$$\sqrt{.909} = .953$$

The square root of a number near 1 is about halfway between 1 and the number.

Interpolation

If it is desired to find the square root of 90.9 more precisely, proceed as follows:

(1) $\sqrt{91}$ (by Table, page 643) = 9.539
(2) $\sqrt{90}$ (by Table) = 9.487
(3) Difference for 1 = .052 ($9.539 - 9.487 = .052$)
(4) Difference for .1 = .0052
(5) Difference for .9 = $9 \times .0052 = .0468$ or .047
(6) $\sqrt{90.9} = 9.487 + .047 = 9.534$.

This procedure is called *interpolation*.

Flying speed changes with altitude

The higher we go and hence the less dense the air, the greater the flying speed that is necessary to sustain a plane of given weight and wing area at the same angle of attack. And we must remember that this greater speed at the same angle of attack requires more horsepower.

EXERCISE 1. At what air speed in miles per hour could the plane in Problem 1 fly at the same angle of attack, at 2600 feet, where the density is .0022 slug per cubic foot?

Take-offs and landings at high altitudes

We see from the discussion above that take-offs and landings at airports of high altitude are affected by the decreased density.

PROBLEM 2. If a plane takes off at 50 miles an hour and lands at 35 miles an hour at sea level, what air speed must it have to take off and land at the same angles of attack at Albuquerque, where the altitude is 5400 feet?

SOLUTION. Solve the formula $A_n = \sqrt{\frac{\rho_o}{\rho_n}}\, A_o$ in each case.

1. $\rho_o = .002378$,
2. ρ_n (for 5400 feet) $= .002025$ (by interpolation),[1]
3. Hence $\sqrt{\frac{\rho_o}{\rho_n}} = \sqrt{\frac{.002378}{.002025}} = \sqrt{1.174} = 1.084$.
4. For take-off $A_o = 50$.
5. $A_n = 1.084 \times 50 = 54.2$.
6. For landing $A_o = 35$.
7. $A_n = 1.084 \times 35 = 37.9$.

[1] The interpolation is done as follows:
ρ for 5000 feet $= .002049$
ρ for 6000 feet $= .001988$
Difference for 1000 feet $= .000061$ $(.002049 - .001988 = .000061)$
Difference for 100 feet $= .000006$
Difference for 400 feet $= .000024$
ρ for 5400 feet $= .002049 - .000024 = .002025$

We see, therefore, that to take off at Albuquerque would require an air speed of about 54 miles an hour and that to land would require an air speed of about 38 miles an hour.

Longer runways are needed at airports at high elevations. Albuquerque has two runways, one 6600 feet long and one 5280 feet long.

EXERCISE 2. For the plane of Problem 2, what air speeds would be necessary to take off and land at Mexico City, which has an altitude of 7444 feet?

More flying speed needed on warm days

Warm air is less dense than cold air, as you will learn in Part IV. For this reason more flying speed is needed on warm days than on cold days. We shall make comparisons in some detail later.

Variation of air speed with altitude

In Problem 2 of Chapter 15 we found the various air speeds at which a given light plane would need to fly, at various angles of attack at 5800 feet, in order that the lift would sustain the weight. We found that at 2° angle of attack the plane would need to fly at 79 miles an hour. Let us investigate the air speeds necessary at 2° angle of attack at other altitudes.

PROBLEM 3. If a plane must fly at 79 miles an hour at 2° angle of attack at 5800 feet (where $\rho = .0020$), what air speed will be required at the same angle of attack at each of the following altitudes?

(1) sea level
(2) 2600 feet ($\rho = .0022$),
(3) 9200 feet ($\rho = .0018$),
(4) 13,000 feet ($\rho = .0016$), and
(5) 17,000 feet ($\rho = .0014$).

SOLUTION. Solve the formula $A_n = \sqrt{\frac{\rho_o}{\rho_n}}\, A_o$

1. For sea level $\rho_n = .002378$. $\rho_o = .002$
2. $\frac{\rho_o}{\rho_n} = \frac{.002}{.002378} = .841$
3. $\sqrt{\frac{\rho_o}{\rho_n}} = \sqrt{.841} = .917$
4. $A_o = 79$
5. $A_n = .917 \times 79 = 72$ miles an hour

The air speed necessary for this plane at sea level is 72 miles an hour. The solutions for the various altitudes are shown in Table 9.

TABLE 9

SHOWING THE COMPUTATION OF AIR SPEEDS NECESSARY TO FLY A GIVEN LIGHT PLANE AT VARIOUS ALTITUDES, AT 2° ANGLE OF ATTACK

ALTITUDE	ρ_n	$\frac{\rho_o}{\rho_n} = \frac{.002}{\rho_n}$	$\sqrt{\frac{\rho_o}{\rho_n}}$	AIR SPEED
0	.002378	.841	.917	72
2,600	.0022	.909	.953	75
5,800	.0020	1.00	1.00	79
9,200	.0018	1.11	1.05	83
13,000	.0016	1.25	1.12	88
17,000	.0014	1.43	1.20	95

The air speeds of Table 9 necessary at the various altitudes for 2° angle of attack are plotted in Figure 123, as shown by the curve marked 2°. The other curves show corresponding air speeds at other angles of attack.

We see from Figure 123 that for any given angle of attack the air speed needed to sustain the weight of the plane increases with the altitude. The increase is fairly uniform; but the lines in the figure curve slightly to the right, showing that the necessary increase in velocity with altitude is slightly greater in the higher altitudes.

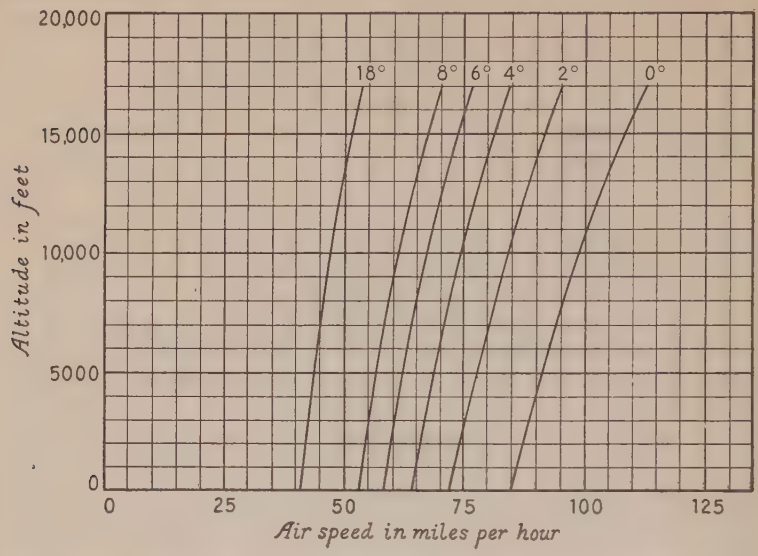


FIG. 123. Graph showing the air speeds necessary to fly a given light plane at various altitudes at various angles of attack.

However, as we increase the angle of attack the necessary air speed is less, as we found to be the case for 5800 feet in Problem 2 of Chapter 15.

Change of angle of attack with altitude

We see from Figure 123, however, that if a plane flies at 85 miles an hour at 0° angle of attack at sea level, it is not necessary to increase the air speed in order to fly at a higher altitude. The plane can fly at a higher angle of attack at the same speed.

For example, at 85 miles an hour the plane can fly at 2° angle of attack at a little over 10,000 feet. If it has sufficient power to fly at 3° angle of attack at 85 miles an hour, it can fly at about 14,000 feet.

EXERCISE 3. Find the air speed necessary to fly the plane of Problem 3 at 0° angle of attack at 1100 feet; at 4200 feet;

at 7500 feet. Check by seeing whether your results will fall on the graph for 0° in Figure 123.

EXERCISE 4. Find the air speed necessary to fly the plane of Problem 3 at 1° angle of attack at the altitudes used in Table 9. The plane must fly at 85 miles an hour at 1° angle of attack at 5800 feet.

EXERCISE 5. Draw a graph similar to the graphs in Figure 123, showing the results you obtained in Exercise 4.

Horsepower needed for altitude

Since it seems evident that a light plane would not have the horsepower necessary to attain all the air speeds shown in Table 9 and Figure 123, we need to find the horsepower required for flying at various altitudes at various angles of attack.

To this end we have the following formula for use when we know the horsepower needed at one altitude.

$$H.P._n = \sqrt{\frac{\rho_o}{\rho_n}} \times H.P._o$$

(Formula for change of horsepower with air density at same angle of attack)

in which —

$H.P._n$ = new horsepower,
$H.P._o$ = old horsepower,
ρ_n = new density,
ρ_o = old density.

The formula shows that the necessary horsepower varies inversely in proportion to the square root of the density — just as the air speed does.

PROBLEM 4. The plane in Problem 1 could fly at 100 miles an hour at 5800 feet. To do so, it required 50 horsepower, let us say. And we found that at 9200 feet it could fly 105.4 miles an hour, at the same angle of attack. What horsepower would be required for this altitude of 9200 feet, at the same angle of attack?

SOLUTION. Solve the formula $H.P._n = \sqrt{\frac{\rho_o}{\rho_n}}\, H.P._o$.

1. $\sqrt{\frac{\rho_o}{\rho_n}} = \sqrt{\frac{.0020}{.0018}} = \sqrt{1.111} = 1.054$
2. $H.P._o = 50$
3. $H.P._n = 1.054 \times 50 = 52.7$

Hence 52.7 horsepower would be required to fly at 9200 feet at the same angle of attack.

EXERCISE 6. What horsepower would be needed to fly the plane of Problem 4 at 2600 feet at the same angle of attack?

EXERCISE 7. A plane requires 70 horsepower to fly at 100 miles an hour at 1100 feet. What air speed in miles per hour and what horsepower would be needed to fly the plane at 9200 feet altitude at the same angle of attack?

CHANGE OF WING AREA

We have investigated thoroughly enough for the present the performance of an airplane of given size and weight at possible air speeds, and the horsepower needed for such at various angles of attack and at various altitudes. Now let us consider a problem the airplane designer might have to consider; namely, the effect of change of size and weight on required velocity and horsepower.

Effect of change of wing area upon required velocity

To find the effect of change of wing area on air speed and horsepower, we have the following formulas:

$$A_n = \sqrt{\frac{S_o}{S_n}}\, A_o$$ (Formula for change of required air speed with wing area)

and $$H.P._n = \sqrt{\frac{S_o}{S_n}}\, H.P._o$$ (Formula for change of required horsepower with wing area)

In these formulas S_o is the old wing area and S_n is the new wing area.

PROBLEM 5. A plane with 200 square feet wing area weighs 2500 pounds, and requires 50 horsepower to fly at 100 miles an hour at a given altitude and angle of attack. What change would be made in the required air speed and required power to fly at the same altitude and angle of attack, if the wing area were increased to 220 square feet?

SOLUTION. Solve the formulas:

$$A_n = \sqrt{\frac{S_o}{S_n}}\,A_o, \text{ and } H.P._n = \sqrt{\frac{S_o}{S_n}}\,H.P._o.$$

1. $A_o = 100$ miles an hour
2. $S_o = 200 \quad S_n = 220$
3. $\frac{S_o}{S_n} = \frac{200}{220} = .909$
4. $\sqrt{.909} = .953$
5. $A_n = .953 \times 100 = 95.3$ miles an hour
6. $H.P._o = 50$
7. $.953 \times 50\ H.P. = 47.7\ H.P.$

With an increase of wing area from 200 to 220 square feet, the air speed could be decreased from 100 to 95.3 miles an hour and the power decreased from 50 to 47.7 *H.P.*

EXERCISE 8. In Problem 5 what effect would a reduction from 200 to 180 square feet of wing area have on the air speed and horsepower necessary to fly at the same angle of attack at the same altitude?

CHANGE OF WEIGHT

We say that the velocity and horsepower vary *inversely* as the square root of the ratio of the new area to the old area. That means that the greater the wing area the less the velocity and the horsepower needed for flying at a given angle of attack and altitude, assuming the weight to be the same. If the new area is four times the old area, the square

root of the ratio (4) equals 2. Hence the velocity and horsepower necessary to fly the larger plane at the same angle of attack would be just half the old velocity and horsepower, assuming that the weight had not been increased.

But we know that if we made a second plane with a wing area four times as large as the first, the weight would be much greater. Let us see, then, what effect change of weight has on velocity and horsepower at a given angle of attack and altitude. Let us consider change of weight alone first, then a change of size and weight.

Effect of change of weight

To find the effect of change of weight alone on the necessary air speed and horsepower, we have the following formulas:

$$A_n = \sqrt{\frac{W_n}{W_o}}\, A_o$$

(Formula for change of air speed with weight at same angle of attack)

and $$H.P._n = \frac{W_n}{W_o}\sqrt{\frac{W_n}{W_o}}\, H.P._o$$

(Formula for change of horsepower with weight at same angle of attack)

In these formulas the W_n is in the numerator of the fraction. Hence the more the weight the more the air speed and horsepower. The air speed necessary to sustain the weight of the plane varies directly (not inversely) as the square root of the weight.

The necessary *horsepower*, however, varies directly as the weight times the square root of the weight.

In Problem 5 we increased the wing area 10 per cent and found the air speed and horsepower necessary to fly the plane at the same angle of attack to be decreased about 5 per cent (to .953).

Let us see what happens when there is an increase in the weight of the same plane instead of in the wing area.

PROBLEM 6. A plane weighing 2500 pounds with 200 square feet wing area can fly at 100 miles an hour on 50 horsepower at a given altitude and angle of attack. What air speed and horsepower will be required to fly the plane at the same altitude and angle of attack if the weight is increased to 2750 pounds (10 per cent)?

SOLUTION. Solve the formulas

$$A_n = \sqrt{\frac{W_n}{W_o}} A_o \quad \text{and} \quad H.P._n = \frac{W_n}{W_o}\sqrt{\frac{W_n}{W_o}} H.P._o$$

1. $\frac{W_n}{W_o} = 1.10$

2. $\sqrt{\frac{W_n}{W_o}} = \sqrt{1.10} = 1.049$

3. $A_o = 100$

4. $A_n = 1.049 \times 100 = 104.9$ miles an hour (new required air speed)

5. $H.P._o = 50$

6. $H.P._n = 1.10 \times 1.049 \times 50 = 57.7$ (new required horsepower)

We see that increasing the weight 10 per cent increases the air speed (necessary to lift the weight) by about 5 per cent. But the necessary horsepower is increased about 15 per cent (7.75 increase in $H.P.$ = about 15 per cent of 50).

EXERCISE 9. What change in air speed and horsepower would be required if the weight of the plane in Problem 6 were changed from 2500 pounds to 2000 pounds? to 2250 pounds?

Wing loading

The number of pounds of weight of a plane per square foot of wing area is called the *wing loading* of the plane. If a plane weighs 2500 pounds and has a wing 200 square feet, we can divide 2500 by 200 and find that there are 12.5 pounds of weight for each square foot of wing area. The wing loading of this plane, then, is 12.5 pounds per square foot.

The symbol for wing loading, therefore, is W/S, meaning $W \div S$.

The formula for finding the velocity necessary to sustain the weight of a plane under given conditions is

$$V = \sqrt{\frac{W}{C_L \frac{\rho}{2} S}}$$

We can write this as

$$V = \sqrt{\frac{W/S}{C_L \frac{\rho}{2}}}$$

Now it is obvious that if we do not change the value of the numerator W/S in the formula (nor the denominator) we do not change the value of V. This means that we can increase both weight and wing area, but so long as the wing loading remains the same, no more velocity is needed. This seems reasonable when we realize that each square foot of wing area can sustain a given weight at a given velocity no matter how many such square feet there are.

Required velocity varies as wing loading

The formulas for change of velocity with weight and with wing area can be combined into one as follows:

$$V_n = \sqrt{\frac{(W/S)_n}{(W/S)_o}} \times V_o, \text{ or } A_n = \sqrt{\frac{(W/S)_n}{(W/S)_o}} A_o$$

Variation of horsepower with change of size and weight

We saw that we could double the wing area and weight without affecting the velocity necessary to sustain the plane. However, if we double the area and double the weight we double the necessary horsepower even to fly at the same velocity. This is because doubling the wing area multiplies the required horsepower by $\sqrt{\frac{1}{2}}$, whereas doubling the weight multiplies the required horsepower by $2\sqrt{2}$; hence doubling both multiplies the required horsepower by $2\sqrt{2} \times \sqrt{\frac{1}{2}}$ which equals 2.

TABLE 10. SPECIFICATIONS AND PERFORMANCE OF VARIOUS AIRCRAFT

	Specifications						Performance					
	Rated horse-power	Wing span	Length	Wing area	Gross weight	Fuel capacity (gallons)	Maximum speed (m.p.h.)	Cruising speed	Landing speed	Cruising range (miles)	Climbing rate (feet first minute)	Service ceiling [1]
Piper Cub J3	65	36′	22′ 3″	178	1,100	12	92	82	35	260	650	12,000
Aeronca Super Chief	65	36′	20′ 10″	169	1,200	17	105	95	38	350	550	15,000
Tailorcraft B 12	65	36′	22′	167	1,200	12	105	95	35	375	600	15,000
Stinson Voyager	90	34′	21′ 8″	155	1,625	20	115	110	47		600	13,000
Monocoupe 90A	90	32′	20′ 6″	132.3	1,610	28	130	110	40		900	15,000
Rearwin Speedster	125	32′	22′ 10″	143.2	1,700	34	150	130	48	550	1,300	18,000
Fairchild M–62A	175	36′	27′ 8″	200	2,450	45	135	120	48	480	835	16,000
Waco YPT–14	220	30′	23′ 1″	244	2,650	50	126	105	55	350	800	13,000
Explorer PC–4	420	38′ 6″	27′ 9″	258	4,000	110	215	150	60	2,150	1,180	30,000
Lockheed 12A	800	49′ 6″	36′ 4″	352	8,650	200	225	212	65	824	1,360	22,300
Vultee P–48C	1,200	36′	28′	197	6,182	139	350	299	77	700	3,500 [2]	33,000
Douglas	1,200	95′	64′ 6″	987	24,800	822	218	188	70	1,080	1,200	22,750
Stratoliner	1,100	107′ 3″	74′ 4″	1,486	45,000	1,700	246	212	70	1,040	1,190	26,200
Clipper Ship	6,200	150′	106′	2,867	84,400	5,460	190	150	69	4,800	800	15,000

[1] Height at which the plane can still climb at 100 feet a minute.

[2] Estimated: data given as 15,000 feet in five minutes.

Exercise 10. If a plane weighing 1200 pounds with a wing area of 180 square feet requires an air speed of 80 miles an hour for lift at a given angle of attack, what air speed would be needed if the weight were increased to 1300 pounds and the wing area were reduced to 170 square feet?

Specifications and performance

Table 10 gives some of the specifications and performances of three popular light planes and a few of the heavier ones. See *Aviation* for February, 1941, and *Aero Digest* for March, 1941, for much more extensive data of this sort. Make up additional exercises, using the data of Table 10, and solve them.

Questions

1. What effect does change of altitude have upon the velocity required to fly a plane?
2. What is the formula for the change of velocity with change of density?
3. How would you find the square root of a decimal such as 2.345?
4. How would you find the square root of a decimal such as .876?
5. What is meant by interpolation? Give an example.
6. What difference is there as to velocity between a take-off at Albuquerque, New Mexico, and one at La Guardia Field, New York?
7. What effect does warm damp weather have upon take-offs?
8. What is the formula for the change of horsepower necessary with change of air density, at the same angle of attack?
9. What effect does change of wing area have upon required velocity and horsepower?
10. What effect does change of weight have upon required velocity?
11. What effect does change of weight have upon required horsepower?
12. What is meant by wingloading?

17

ENGINES AND PROPELLERS

IN CONNECTION with a discussion of power it is well to understand how power is produced by the engine and converted by the propeller into thrust.

It is not the purpose of this book to deal at length with engines or propellers, but you should understand a few of the basic principles of the four-stroke-cycle gasoline engine [1] used in airplanes, and of propeller efficiency.

THE ENGINE

The four-stroke cycle

As you know, the source of power is the explosion of gasoline vapor in the cylinders of the engine. An engine may have any number of cylinders — even as high as twenty-four.

Figure 124 shows four views of a single cylinder illustrating the four-cycle stroke.

A cylinder is a cylindrical cell (*a*) containing a close-fitting piston (*c*) which moves back and forth in the cylinder, moved by a connecting rod joined to the crankshaft in housing (*b*). Each cylinder has two valves,[2] an intake valve (*f*) and an exhaust valve (*e*).

The four strokes are the —

(1) intake stroke,
(2) the compression stroke,
(3) the power stroke or working stroke, and
(4) the exhaust stroke.

[1] The type of engine referred to here is known as the Otto-cycle engine as distinguished from the Diesel-cycle engine.

[2] In some cases two intake and two exhaust valves are used.

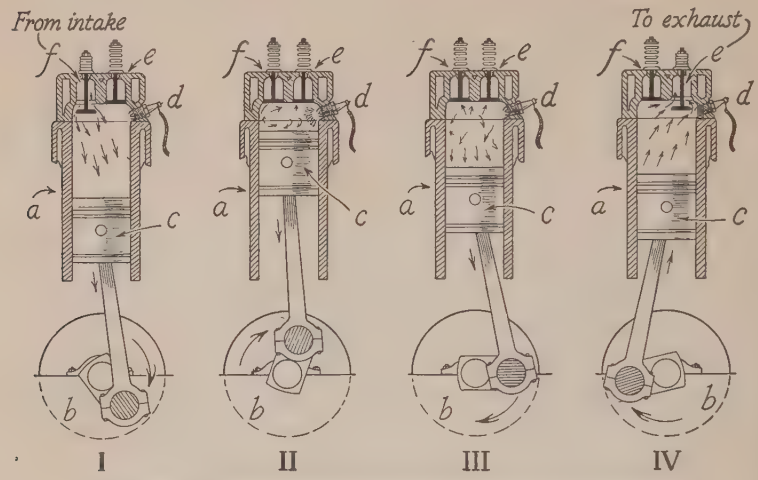


FIG. 124. The four strokes of a four-stroke-cycle engine.

On the intake stroke the intake valve is open. The piston is expanding the chamber of the cylinder, and the mixture of gasoline vapor and air is being sucked into the cylinder from the carburetor.

On the compression stroke both the intake and the exhaust valves are closed. The piston contracts the chamber and compresses the fuel.

Near the beginning of the working stroke the spark is generated in the spark plug (*d*) which projects into the cylinder chamber, the spark igniting the fuel. The valves are closed and the fuel explodes, thus furnishing the power to drive the piston and expand the chamber.

On the exhaust stroke the exhaust valve is open and the piston contracts the chamber, expelling the burnt fuel.

A common number of cylinders for the engine of a light plane is four. The connecting rods from the four pistons are all connected to the crankshaft or drive shaft which drives the propeller. One cylinder is firing during each of the four strokes of each cylinder, thus furnishing the power for the

intake, compression, and exhaust strokes of the other three cylinders.

When there are only two cylinders, one cylinder fires as the other intakes, and the pistons then depend upon the momentum of the crankshaft and propeller to furnish the power to make the compression and exhaust strokes.

On the other hand, if there are eight cylinders, these all fire during two revolutions of the crankshaft. Hence, equally spaced, the cylinders fire at intervals of one fourth of a revolution. Since the power stroke of each cylinder lasts one half a revolution of the crankshaft, there is a 50 per cent *power overlap.*

Required versus available horsepower

Heretofore we have considered only the horsepower *required* of the propeller to propel a plane at the velocity necessary for the required lift. We need to consider also various conditions affecting *available* horsepower.

Torque and thrust horsepower

We have seen how an airplane in a given condition of flight requires thrust delivered at a given rate. This we call *thrust horsepower.* But the engine merely produces what is called *torque horsepower.*

The word "torque" refers to twist, and torque horsepower means the horsepower residing in the twist of the crankshaft or drive shaft produced by the firing of the fuel in the cylinders.

Purpose of the propeller

We may say, therefore, that the purpose of the propeller is to convert torque horsepower into thrust horsepower.

As explained below, various considerations affect the amount of available horsepower the engine transmits to the

propeller. Two important considerations affecting available horsepower are —

(1) air density (altitude or air temperature), and

(2) the number of revolutions per minute of the engine.

The number of revolutions per minute (*RPM*) of the engine is affected by the size of the propeller, the angle of attack of the propeller blades, the load on the engine, etc.

Loss of power with altitude

As a plane flies higher and higher, the air becomes less dense, as you know; and even though the cylinders draw in a cylinderful of air at each intake stroke, there are fewer slugs of air drawn in, and therefore less oxygen. It takes oxygen to burn gasoline vapor; and the less the oxygen, the less the power.

Figure 125 shows the reduction in power with altitude. The scale at the left shows the per cent of the sea-level horse-

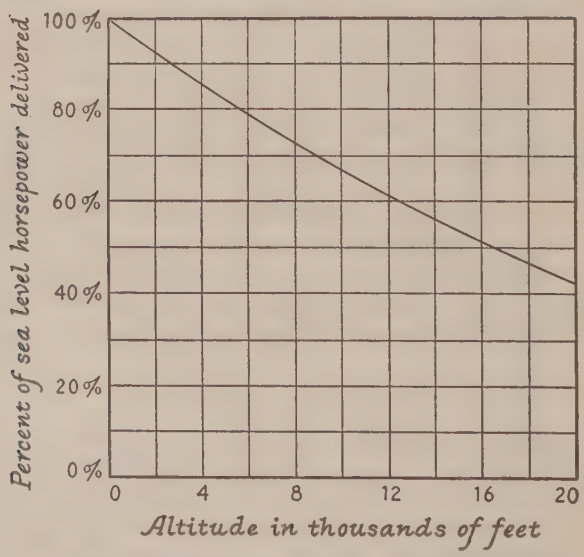


FIG. 125. Graph showing the per cent of sea-level horsepower available at various altitudes.

power which is delivered at altitude. We see, for example, that at 5000 feet the power is reduced to about 80 per cent; at 10,000 feet, to about 65 per cent; and at 20,000 feet, to less than half.

This reduction in power with altitude is one of the limitations on the attainable altitude of an unsupercharged engine. The common light training plane can climb to only about 14,000 feet; but with a supercharged engine a plane can fly much higher.

Variation of available horsepower with number of revolutions per minute

The horsepower that an engine can deliver directly to the crankshaft is called the *brake horsepower*. The brake horsepower of an engine is independent of the type of propeller used on the plane.

The brake horsepower of an engine changes with the number of revolutions per minute (*RPM*). Figure 126 shows the change of available horsepower with revolutions per minute for a typical engine.

Note that the available horsepower increases with increase in *RPM* up to 2500 *RPM* and thereafter diminishes. The 2500 *RPM* is, then, the *RPM* for maximum horsepower of this engine.

We see, therefore, that a plane must be equipped with a propeller of such size and

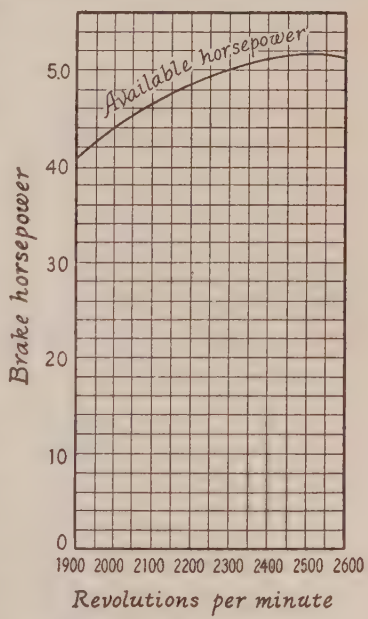


FIG. 126. Graph showing the available brake horsepower of a typical engine at full throttle at various numbers of revolutions per minute.

other characteristics that the engine will turn at approximately the most efficient *RPM* under normal conditions.

If the propeller is too large for the engine, the speed of the engine will be too slow for efficiency. If the propeller is too small for the engine, the engine will race and lose efficiency because of too great an *RPM*.

THE PROPELLER

The propeller as an airfoil

A propeller consists of two or more *blades* connected to a *hub* at the center, as shown in Figure 127. Each blade is an airfoil in the same sense that a wing is. It has a *leading edge* and a *trailing edge*.

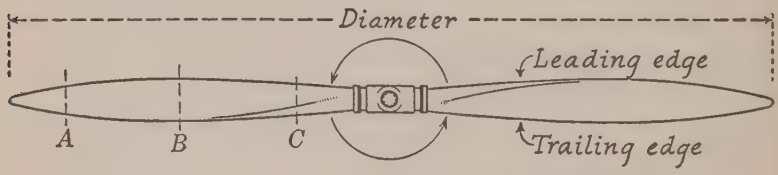


FIG. 127. Front view of a typical propeller.

Since the propeller is twisted, so to speak, it has no single angle of incidence like a wing. Instead, each *blade element* (or slice) of the blade has its own individual *blade angle*.

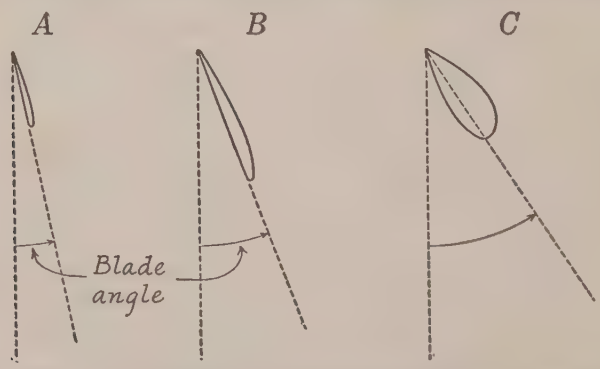


FIG. 128. Blade angles of the propeller shown in Figure 127.

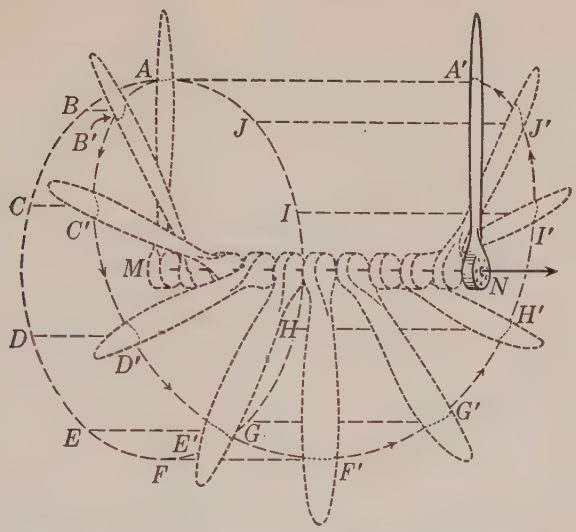


FIG. 129. The rotational and forward motions of a propeller blade.

Blade elements at A, B, and C of Figure 127 are shown in Figure 128, each with its respective blade angle. The *blade angle* of an element of the blade is the angle that the *chord* of the blade element makes with a plane perpendicular to the propeller shaft.

The blade element that is situated just three fourths of the distance from the axis to the tip is called the *nominal element.* The blade angle of this element is called the *nominal-blade angle.* (See also Fig. 130.)

Forward motion of the propeller

Figure 129 shows the forward motion of the propeller as it makes one revolution. The dotted curve $ABC \cdots A$ shows the path the nominal element would make if the axle were stationary. The curve $AB'C' \cdots A'$ shows the path through the air that the nominal element actually makes while the plane is flying. Note that during one revolution the pro-

peller axle moves forward the distance MN, and the nominal blade element moves forward the distance AA', equal to MN.

Figure 130 shows the curves $ABC \cdots A$ and $AB'C' \cdots A'$ laid out flat.

Pitch of the propeller

The *pitch* of a propeller is the distance AA' in feet that the axle of the propeller moves forward with the plane during one full revolution, when the nominal-blade element is meeting the air at zero angle of attack. This pitch is sometimes called the *nominal pitch.*

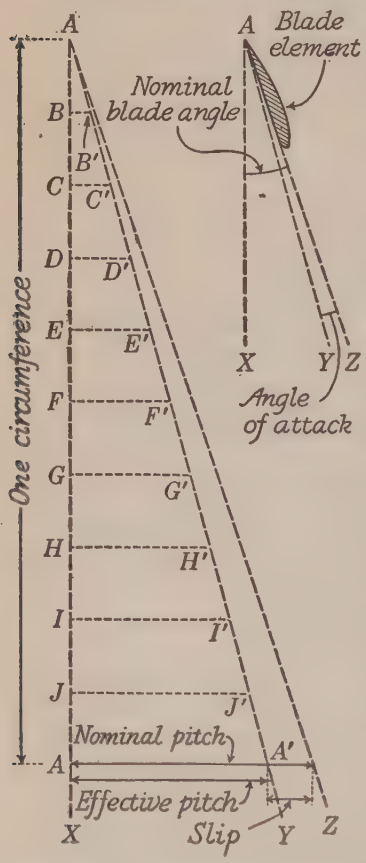


FIG. 130. The pitch of a propeller.

Effective pitch

Although the propeller has some thrust at zero angle of attack, just as a cambered wing has some lift at zero angle of attack, the propeller usually turns at such a rate in relation to the air speed of the plane that the angle of attack is slightly positive. This means that the forward movement of the plane and of the propeller axle during one full revolution is somewhat less than the nominal pitch of the propeller. This lesser distance is called the *effective pitch,* and the amount of lag — the difference between the effective pitch and the nominal pitch — is called the *slip* of the propeller.

The most efficient angle of attack

We have already seen how the ratio (L/D) of the lift to the drag of a wing changes with angle of attack. We saw that at 1° or 2° the ratio L/D was greatest. This ratio is sometimes thought of as a measure of the efficiency of the wing.

Similarly, in the case of a propeller, the lift-over-drag ratio (L/D) is greatest — the efficiency is at maximum — when every part of the propeller meets the air at its most effective angle of attack.

When a propeller is turning on a stationary axle, the angle of attack exceeds the efficient angle of attack throughout the length of the blades, the excess being greatest near the hub. If the plane is moving at a greater air speed than that designed for the propeller, the angle of attack throughout the length of each blade is less than the most efficient angle. It may even be negative, as in a dive where gravity is propelling the plane at a rate faster than the turning of the propeller can keep up with, so to speak.

Propeller design and adaptation

Therefore, a propeller must be constructed as to pitch to fit the horsepower of the engine, so that under normal flying conditions the propeller will be meeting the air at its most efficient angle of attack.

Cruising and climbing propellers

A propeller can be constructed to have its best angle of attack either in a climb or at level flight. In the first case we can call the propeller a *climbing propeller*, and in the other case a *cruising propeller*.

Loss of horsepower by the propeller

Clearly, the propeller can be a cause of loss of horsepower. Since the pitch of an ordinary propeller cannot be changed to

fit changing conditions, as of air speed, horsepower will be lost when the propeller is not meeting the air at the most efficient angle of attack.

Airplane design

An airplane-engine-propeller combination is so adjusted by the designer that when the airplane is cruising at moderate altitude the wing will be at its most efficient angle of attack, the engine will be turning at its most efficient *RPM*, and the propeller will be *pitched* at its most efficient angle of attack.

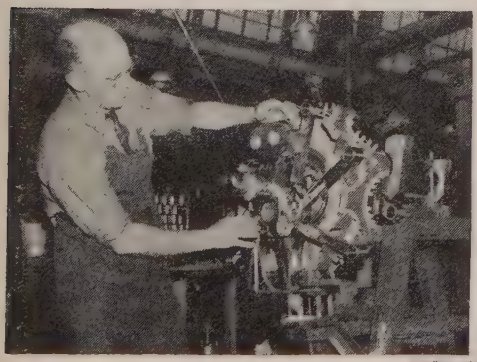
Loss of efficiency during climb

During a climb, (1) the airplane is at a higher angle of attack, (2) the engine is turning more slowly (laboring), and (3) the propeller is slowed up (too steeply pitched since the air speed is slow). In all three ways there is less efficiency. The wing size and the size and pitch of propeller could be designed, of course, to give their greatest efficiency in the climbing position; but since an airplane cruises during a much greater part of its flying time than it climbs, it is designed to be at its maximum efficiency in cruising.

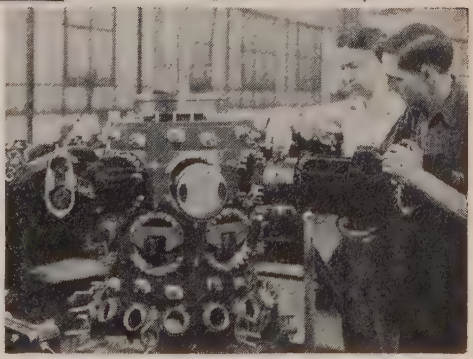
Questions

1. What are the four strokes of a four-stroke-cycle engine?
2. What happens on the intake stroke?
3. What happens on the compression stroke?
4. What happens on the power stroke?
5. What happens on the exhaust stroke?
6. Where does a piston get the power to compress the fuel gas?
7. What factors influence the output of power by the engine? by the propeller?
8. What is meant by torque horsepower?
9. Complete this sentence: The propeller converts torque horsepower . . .
10. What three important considerations affect the amounts of available horsepower?

11. What is meant by *RPM*?
12. Can you explain the effect of change of *RPM* on available horsepower?
13. In what way must the propeller be adapted to the engine?
14. In what way may a propeller be considered as an airfoil?
15. What is a blade element?
16. What is the normal-blade angle?
17. What is the nominal pitch of a propeller?
18. What is the effective pitch of a propeller?
19. What is the slip?
20. Is the angle of attack the same along the blade of a propeller? Explain.
21. How may horsepower be lost because of the propeller?



Wright Aeronautical Corporation



FIGS. 131 and 132. Assembling airplane engines.

18

CLIMBING AND CIRCLING

IT IS of interest and value to understand the laws governing rate of climb of an airplane and also the laws governing flight in a curved path.

Required horsepower less than that available

Let us say that the horsepower required by a plane of given wing area and weight to fly level at 60 miles an hour is 17, and the engine develops 32 available horsepower at that velocity. This means that the difference between 17 and 32, or 15 *H.P.*, is available for use in climbing.

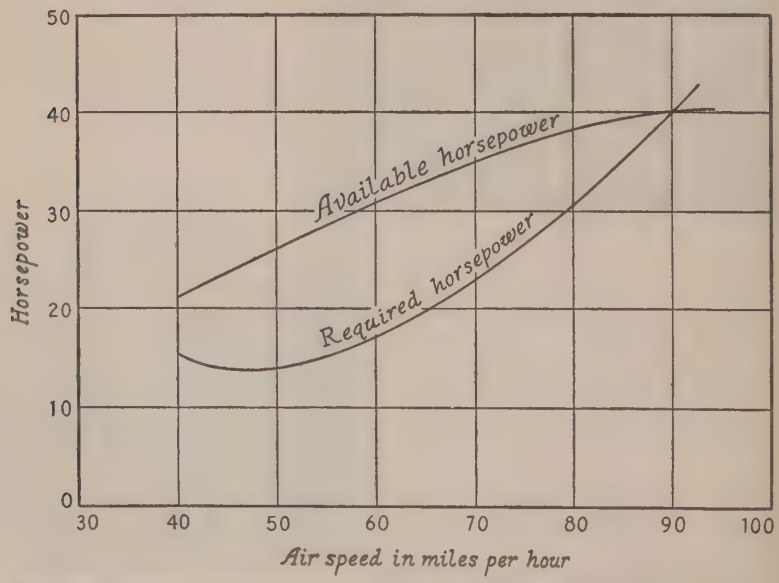


FIG. 133. Correspondence between required and available horsepower.

Figure 133 shows the horsepower required and the horsepower available for flying at various air speeds at sea level by a light plane of given weight, wing area, and engine.

Since the curves intersect at a point representing about 90 miles an hour, it shows that no surplus power is available for climbing at 90 miles an hour. Hence the plane cannot climb at that air speed.

From Figure 133 we see that at 70 miles an hour the plane in question requires 23 *H.P.* to sustain it in level flight at sea level, and that at that velocity it has 35.5 *H.P.* available. This means that to fly level the throttle may be adjusted so that the engine develops only 23 *H.P.*, leaving 12.5 *H.P.* in reserve. It means also that at sea level the plane can begin to climb at 70 miles an hour. It can continue to climb as fast as any surplus horsepower will permit.

Horsepower for climbing

You have already learned that one horsepower is the power to do 550 foot pounds of work per second. This is at the rate of 33,000 foot pounds per minute ($60 \times 550 = 33{,}000$). It means that one horsepower can lift one pound 33,000 feet in a minute; or that it can lift 33,000 pounds one foot in a minute; or that it can lift 3300 pounds 10 feet in a minute. The rate of lift is such that the weight in pounds times the number of feet of lift per minute equals 33,000.

Figure 133 pertains to a plane weighing 1100 pounds. One horsepower can lift the plane at the rate of 30 feet per minute ($33000 \div 1100 = 30$). Since 12.5 *H.P.* are available for lifting the plane at 70 miles an hour, the plane can be lifted 12.5 times 30, or 375 feet, per minute at 70 miles an hour.

Figure 134 shows the rate of climb of the 1100-pound plane at various air speeds at sea level, and at 5000 feet altitude. It shows, for example, that at sea level the plane can climb at 300 feet per minute at 45 miles an hour; at about 365 feet per minute at 50 miles per hour; and so on.

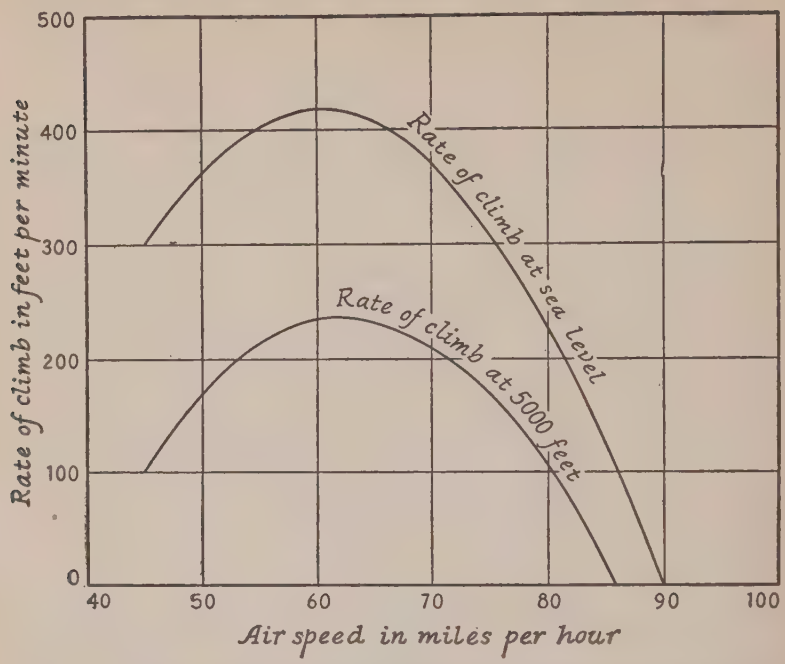


FIG. 134. Graph showing the correspondence between rate of climb and air speed, at sea level and at 5000 feet.

Of course, when we speak of rate of climb at sea level in feet per minute, we refer to the rate of climb at the moment the plane is at sea level, as though the plane took off from an airport below sea level and were in process of climbing as sea level was reached. A plane can have a given rate of climb at any precise moment, even though the rate changes to a lesser rate the next moment.

Maximum rate of climb

We see that the maximum rate of climb for this plane is obtained, both at sea level and at 5000 feet, when the plane has an air speed of about 60 miles an hour, the rate of climb being about 420 feet per minute at sea level and about 235 feet per minute at 5000 feet. The pilot must realize, there-

fore, that the best rate of climb is at a speed of only about two thirds the maximum speed possible for level flight. If he is climbing at 70 or 80 miles an hour, he should lift the nose higher until the air-speed indicator shows 60 miles an hour to get the fastest climb.

Change of rate of climb with altitude

Figure 134 shows also that at 5000 feet altitude the plane can climb at only 100 feet per minute at 45 miles an hour; at about 170 feet per minute at 50 miles per hour; and so on.

The curve for 5000 feet altitude was derived from curves similar to those of Figure 133 showing the available horsepower and required horsepower for various air speeds at 5000 feet.

Experiments show that the maximum rate of climb decreases by about the same amount with each 1000 feet of altitude. Thus, the straight line in Figure 135 shows the maximum rate of climb at various altitudes for the light plane mentioned above. It shows, for example, that the plane can climb 420 feet a minute at sea level, 382 feet a minute at 1000 feet, 344 feet a minute at 2000 feet, and 0 feet a minute at 11,000 feet.

This graph in Figure 135 was obtained by first drawing a series of curves, as in Figure 134, one for each altitude, and finding the maximum climbing rate at each altitude.

The curve in Figure 135 shows the number of minutes required to climb 1000 feet at the rate of climb at sea level, at 1000 feet, and so on. At the rate of climb at sea level 2.4 minutes would be required to climb 1000 feet; at the rate of climb at 1000 feet, 2.6 minutes would be required to climb 1000 feet; and at the rate of climb at 10,000 feet, 26 minutes would be required to climb 1000 feet.

Figure 136 shows the altitude gained in various numbers of minutes. This figure was obtained from the data of the

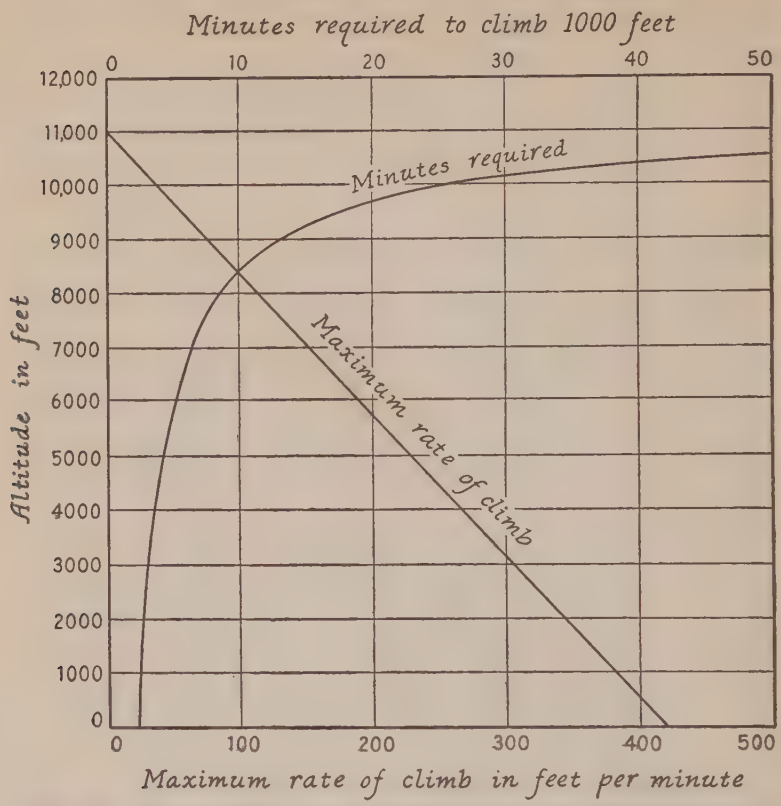


FIG. 135. Graph showing the reduction in rate of climb with increase in altitude.

curve in Figure 135 by noting the time required to climb the first 1000 feet, the second 1000 feet, the third 1000 feet, and so on, and adding to find the time required to climb 1000 feet, 2000 feet, 3000 feet, and so on.

Figure 136 shows that in 10 minutes the plane can reach about 3500 feet altitude, that in 20 minutes it can reach about 5900 feet altitude, and so on. It can reach 10,500 feet in about 80 minutes. Eleven thousand feet is the theoretical *ceiling* which the plane would reach if it kept on climbing indefinitely.

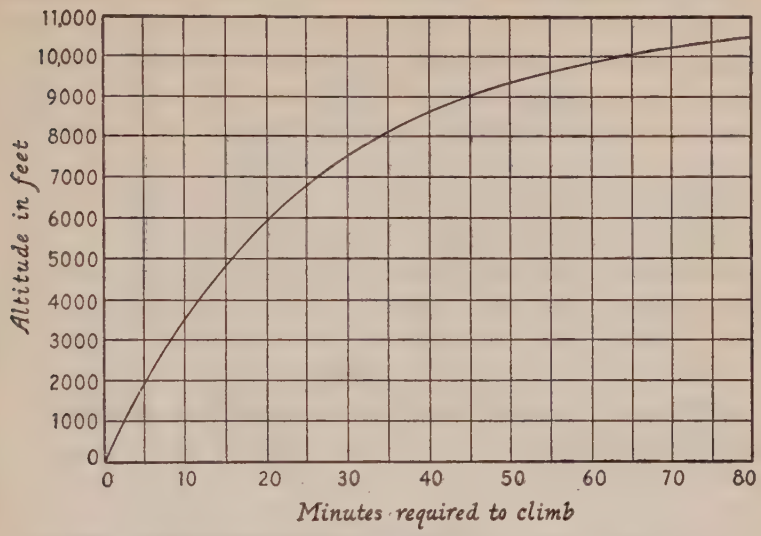


FIG. 136. Graph showing the flying distance required to attain various altitudes.

EXERCISE 1. How long would it take the plane mentioned in this chapter to climb to 5000 feet? 7500 feet? 10,000 feet? (See Fig. 136.)

FLYING A CURVE

Our knowledge of the parallelogram law of forces enables us to determine what happens among the forces acting on a plane when it is flying in a circle.

We have learned that in order to fly on the arc of a circle a centripetal force is needed to overcome the centrifugal force. This centripetal force must be obtained from the lift of the wings, since there is no getting centripetal force in a plane such as by tying one end of a wire to the plane and the other to a pole!

You already know how a pilot gets centripetal force — he banks the plane. The "lift" is then in a slanting direction, giving it a vertical component for sustentation and a horizontal component for the centripetal force.

Thus, if a plane is banked as shown in Figure 137, the lift OL must be sufficient to have a sustentation component OS to balance the weight of the plane OG, and a centripetal component OC to give the plane a turning velocity.

We say that the centripetal force gives the plane an acceleration toward the center of the circle on which it is flying.

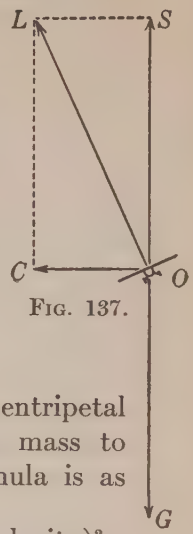


FIG. 137.

Centripetal force needed for a turn

We have a formula for the amount of centripetal force needed to cause a body of a given mass to travel a circle of a given radius. The formula is as follows:

$$\text{Centripetal force needed} = \frac{\text{Mass} \times (\text{Velocity})^2}{\text{Radius}},$$

or $$F = \frac{MV^2}{R} \qquad \text{(Formula for centripetal force)}$$

in which —

F = the centripetal force in pounds,
M = the mass of the body in slugs,
V = the velocity of the body in feet per second

and

R = the radius of the circle in feet.

If a body is traveling a curve at uniform rate, the velocity of the body is the number of feet of curve traversed per second. If it is not traveling at uniform rate, the velocity at any instant is the number of feet the body would travel during the next second if the velocity it had at the given instant remained uniform during that second.

Lift necessary to make a turn

Problem 1 illustrates how to find the lift necessary to make a turn under given conditions.

PROBLEM 1. Let us say that a plane weighs 1200 pounds and is flying a circle with a radius of 1000 feet at a velocity of 123 feet per second. What force of lift is needed to sustain the plane and to furnish the centripetal force? What lift is needed in addition to that needed for straight and level flight? (Assume one slug to weigh 32.2 pounds.) Also what angle of bank will be required?

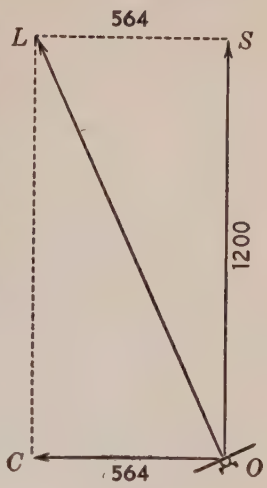


FIG. 138.

SOLUTION. First solve the formula for centripetal force.

$$F = \frac{MV^2}{R}$$

1. M in slugs $= \dfrac{1200}{32.2} = 37.3$ (slugs)
2. $V = 123 \qquad V^2 = 15{,}129$
3. $R = 1000$
4. $F = \dfrac{37.3 \times 15{,}129}{1000} = 564$ pounds

The centripetal force needed is 564 pounds.

5. Now construct a parallelogram of forces as follows (see Fig. 138): Draw vector OS 1200 units long, and vector OC 564 units long. Complete the parallelogram and draw and measure its diagonal OL to find the lift. (OL = about 1330 units. Hence the lift needed is about 1330 pounds.)

6. Additional lift needed = 1330 − 1200 = 130 pounds.

7. Measure angle SOL. It equals the angle of bank. (This is about 25°.)

Arithmetic[1] *method*

In geometry the ancient theorem of Pythagoras is that in any right triangle the sum of the squares of the two sides making the right angle equals the square of the hypotenuse (the side opposite the right angle).

[1] Pronounced ar′ith-met′ic when an adjective.

This means that in the right triangle OSL in Problem 1,

$$(OL)^2 = (OS)^2 + (LS)^2$$

so

$$(OL)^2 = 1200^2 + 564^2$$
$$= 1{,}440{,}000 + 318{,}096$$
$$= 1{,}758{,}096$$

hence

$$OL = \sqrt{1{,}758{,}096} = 1326$$

Therefore the lift needed to fly the circle is 1326 pounds. Our value of 1330 pounds obtained by measurement is close enough for practical purposes to the more exact value obtained by arithmetic.

Exercise 2. How much additional lift is needed for the plane in Problem 1, if the circle flown has a radius of 800 feet?

Exercise 3. In Exercise 2 check the measurement of lift, using the arithmetical method.

Exercise 4. What angle of bank is needed by the plane in Exercise 2?

Finding the lift for an angle of bank

We can use the parallelogram law of forces to find the additional lift needed for a given angle of bank, assuming the angle of bank to be correct for the turn.

Problem 2. What lift is needed for a plane weighing 1200 pounds to make a 70° bank?

Solution. Draw the parallelogram of vectors and find the diagonal. (See Fig. 139.)

1. Draw OS 1200 units long.
2. Draw SX perpendicular to SO.
3. Draw OY at 70° to OS cutting SX at L.
4. Measure OL to find the lift. (OL = about 3500 units. Hence the lift is about 3500 pounds.)

We see, therefore, that a 70° bank requires a lift nearly three times the lift needed for level flight. You can see why

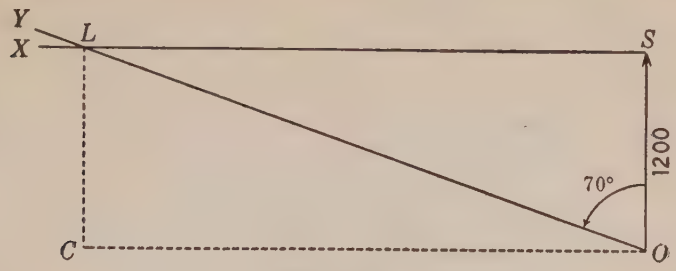


FIG. 139.

an ordinary plane cannot fly a circle continuously at more than about 70° of bank — few planes have sufficient available power.

EXERCISE 5. What additional lift is needed to fly a 1000-pound plane at a 45-degree angle of bank?

Finding the pivotal altitude

We are now able to understand better how to find the pivotal altitude for flying an on-pylon turn; that is, the altitude at which it is necessary to fly in order to fly a circle or arc around a pylon in calm air with the wings (lateral axis) always pointing directly toward the pylon.

PROBLEM 3. At what altitude must a plane weighing 1200 pounds fly in order to fly a circle of 1000 feet radius around a pylon at 100 feet a second, assuming no wind?

SOLUTION. First find the lift needed, then find the angle of bank, then the pivotal altitude.

1. M in slugs $= 1200 \div 32.2 = 37.3$

2. $F = \dfrac{MV^2}{R} = \dfrac{37.3 \times 100^2}{1000} = 373$ pounds

Draw a figure (see Fig. 140) to represent the sustentation OS, the centripetal force OC, the lift OL, the radius OA, and the pivotal altitude PA.

3. Draw vector OS 1200 units long and vector OC 373 units long. Complete the parallelogram and draw diagonal OL. Angle SOL equals the angle of bank.

4. Draw OA horizontal, 1000 units long to represent the 1000-foot radius.

5. Draw OX perpendicular to OL to represent the lateral axis of the plane. Angle XOA is the angle of bank.

6. Draw AY vertical, intersecting OX at P. P is the pylon. PA is the pivotal altitude. Measure it. (It represents about 310 feet.)

The pivotal altitude for this plane at this velocity with this radius is about 310 feet.

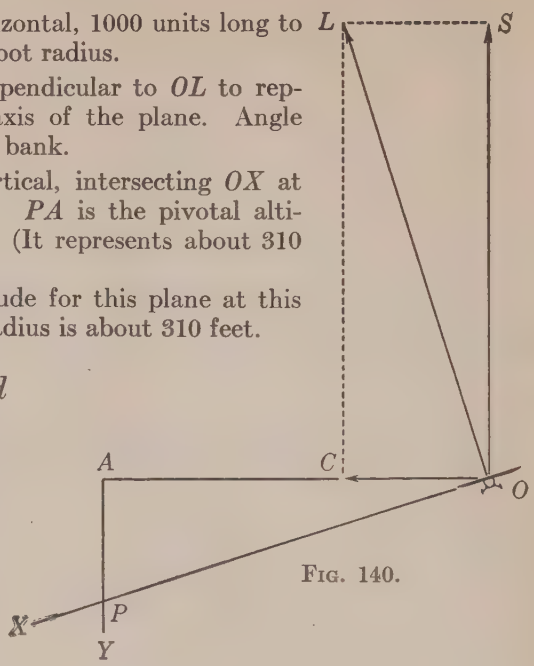


FIG. 140.

Arithmetic method

Now you know just what you are doing to find the pivotal altitude and realize that in Figure 140 triangle PAO is similar [1] to triangle LSO.

Hence $$\frac{PA}{AO} = \frac{LS}{SO};$$

therefore, $$\frac{PA}{1000} = \frac{373}{1200} = .311;$$

hence $PA = 1000 \times .311 = 311$ feet (pivotal altitude). (By measurement we got 310 feet.)

EXERCISE 6. Find the pivotal altitude for a plane weighing 1500 pounds flying a circle with 1000-foot radius at 100 feet per second. Use the graphic method.

[1] "Similar" means having exactly the same shape. If two triangles are similar, their corresponding angles are equal and their corresponding sides are proportional. That is, if two similar triangles have sides a, b, and c and corresponding sides a', b', and c', then $\frac{a}{a'} = \frac{b}{b'} = \frac{c}{c'}$ and $\frac{a}{b} = \frac{a'}{b'}$, $\frac{a}{c} = \frac{a'}{c'}$, and $\frac{b}{c} = \frac{b'}{c'}$.

Also, if the corresponding sides of two triangles are proportional, we know that the triangles are similar and hence that their corresponding angles are equal.

EXERCISE 7. Check the solution to Exercise 6, using the arithmetical method.

Your answer in Exercises 6 and 7 should be about 310 feet. This shows that the pivotal altitude is the same for all planes regardless of weight, so long as they fly at 100 feet per second with a 1000-foot radius.

EXERCISE 8. Find the pivotal altitude for a plane weighing 1200 pounds flying a circle with 2000-foot radius at 100 feet per second. Use the graphic method.

EXERCISE 9. Check your answer to Exercise 8 by the arithmetical method.

Your answers to Exercises 8 and 9 should also be 310 or 311 feet. This shows that the pivotal altitude is the same for all planes and for any radius when flying at 100 feet per second.

Formula for pivotal altitude

The formula[1] for the pivotal altitude (given also in Chapter 3) is as follows:

$PA = .067\ A^2$ (Formula for the pivotal altitude)

in which —

PA is the pivotal altitude in feet, and

A is the air speed of the plane in miles per hour.

[1] The formula is derived as follows:

In Figure 140, $\frac{PA}{AO} = \frac{LS}{SO}$, as explained above under arithmetical method,

$$AO = \text{the radius } R; \text{ so } PA = \frac{LS}{SO} \times R$$

but

$$\frac{LS}{SO} = \frac{\text{Centripetal force}}{\text{Weight of plane}} = \frac{F}{W}$$

so

$$PA = \frac{F}{W} \times R$$

By the formula for centripetal force, $F = \frac{MV^2}{R}$,

so

$$PA = \frac{MV^2}{R} \div W \times R = \frac{MV^2}{W}.$$

(*Footnote is continued on next page.*)

PROBLEM 4. Using the formula, find the pivotal altitude for a plane flying with an air speed of 90 miles an hour.

SOLUTION.
$$\begin{aligned} PA &= .067\,A^2 \\ &= .067 \times 90^2 \\ &= .067 \times 8100 \\ &= 543 \text{ feet} \end{aligned}$$

The pivotal altitude for this air speed is 543 feet.

EXERCISE 10. Find the pivotal altitude for air speeds of 60, 80, 100, 120, 140, 160 miles an hour.

EXERCISE 11. Plot the results of Exercise 10 in a chart, letting the air speed be measured horizontally and the pivotal altitude vertically, and draw a smooth graph.

Drawing a graph

In drawing a graph as in Exercise 11 be sure to —

(1) choose suitable units so the graph will fit into the chart;

(2) write on the margin the scales you use, so the reader can read the chart easily;

(3) label the scales so the reader will know what is being measured; and

(4) give the chart a title.

Your chart for Exercise 11 should look like Figure 141.

EXERCISE 12. From your graph for Exercise 11, find the pivotal altitude for an air speed of 95 miles an hour; for 107 miles an hour.

Now the weight of the plane in pounds equals its mass in slugs $\times$ 32.2; that is, $W = 32.2\,M$.

Hence $$PA = \frac{MV^2}{32.2\,M} = \frac{V^2}{32.2} \text{ when } V \text{ is in feet per second.}$$

$$V \text{ (in feet per second)} = 1.467\,A \text{ (miles per hour)}$$

so
$$\begin{aligned} V^2 &= 1.467^2\,A^2 \\ &= 2.152\,A^2 \end{aligned}$$

hence
$$PA = \frac{2.152\,A^2}{32.2} = .067\,A^2.$$

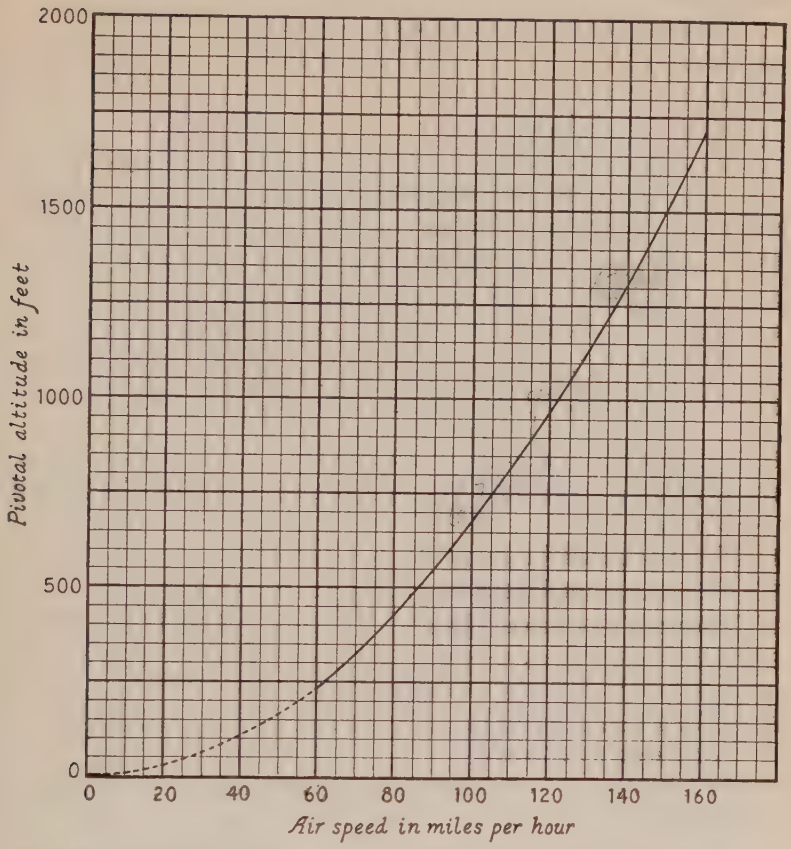


FIG. 141. Graph showing the increase of pivotal altitude with increase in air speed.

QUESTIONS

1. Of what use in an airplane engine is horsepower in excess of that needed for flying level at cruising speed?
2. Distinguish between required horsepower and available horsepower as these terms have been used.
3. How does excess of available horsepower in an airplane engine vary with velocity?
4. What determines possible rate of climb?

5. How does altitude affect rate of climb?
6. What is meant by the ceiling of a plane?
7. What gives a plane a ceiling?
8. What is centripetal force?
9. When is centripetal force needed? What is the relation between centripetal and centrifugal force?
10. In what direction is the force of sustentation?
11. In what direction is the centripetal force in a normal turn?
12. In what direction is the lift in a normal turn?
13. How are the vectors of sustenance, lift, and centripetal force related?
14. What is meant by the formula, $F = \frac{MV^2}{R}$?
15. What is the theorem of Pythagoras?
16. How is the theorem of Pythagoras used to find the lift needed in a turn?
17. What is meant by the pivotal altitude?
18. What is meant by the formula, $P.A. = .067\ A^2$?
19. How can the pivotal altitude of a plane be found?
20. What effect does length of radius of turn have upon the pivotal altitude of an on-pylon turn?
21. How would you find the total lift needed to fly a circle, knowing the angle of bank?
22. What are the four important steps to follow in drawing a graph?

19

SIMPLE TRIGONOMETRY OF AERONAUTICS

TRIGONOMETRY is the science of the measurement of triangles. (*Trigon* = triangle, *metry* = measurement.)

Many persons think of trigonometry as a very difficult subject. It has its difficult aspects, but some trigonometry is very easy, as you will see.

The purpose of this short chapter is to give you an introduction to trigonometry, and to show you how useful simple trigonometry is in dealing with many of the problems of aeronautics.

Finding the angle of bank

Let us begin with the simple problem of finding the angle of bank of a plane that is flying a circle with a given radius and at the pivotal altitude, and that has its lateral axis pointing to a pylon.

PROBLEM 1. A plane is flying an on-pylon turn of 2000-foot radius at the pivotal altitude of 728 feet. What is the angle of bank?

SOLUTION. 1. Draw a sketch of the situation as shown in Figure 142. (It is customary to use the Greek letter β (Beta) to denote the angle of bank. See the Greek alphabet, page 652.)

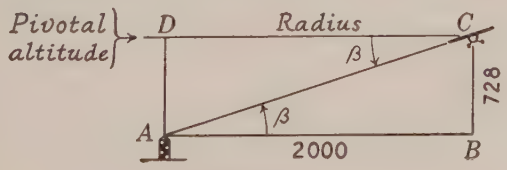


FIG. 142.

2. Find the quotient: $\frac{\text{Side opposite } \beta}{\text{Side adjacent to } \beta}$ in triangle ABC.

$$\text{Side opposite } \beta = 728 \text{ feet}$$
$$\text{Side adjacent to } \beta = 2000 \text{ feet}$$
$$\frac{\text{Side opposite } \beta}{\text{Side adjacent to } \beta} = \frac{728}{2000} = .364$$

3. Look up .364 in the accompanying Table of Tangents (Table 11 *a*) and find the angle corresponding. (It is 20°.)

The angle of bank is 20°.

TABLE 11 *a*

TABLE OF TANGENTS

ANGLE	TANGENT $\frac{\text{(Side opposite)}}{\text{(Side adjacent)}}$
10°	.176
20°	.364
30°	.577
40°	.839
50°	1.192
60°	1.732
70°	2.747
80°	5.671

Tangent of an angle

A triangle with a right angle is called a *right triangle*. An angle that is less than a right angle is called an *acute angle*. If the length of the side opposite an acute angle of a *right triangle* is divided by the length of the side adjacent to that same angle, the quotient is called the *tangent* of *that* angle.

In a right triangle

$$\frac{\text{Side opposite an acute angle}}{\text{Side adjacent to the angle}} = \text{Tangent of the angle.}$$

The tangent of 30° is often written tan 30°.

EXERCISE 1. What is the angle of bank of a plane making an on-pylon turn if the radius is 2000 feet and the pivotal altitude is 1154 feet?

EXERCISE 2. What is the angle of bank if the radius is 3000 feet and the pivotal altitude is 2517 feet?

EXERCISE 3. What is the angle of bank if the radius is 1500 feet and the pivotal altitude is 264 feet?

PROBLEM 2. What angle of bank is needed if a plane weighs 1200 pounds and requires 692 pounds of centripetal force?

SOLUTION. See Figure 143.

1. $\dfrac{\text{Side opposite } \beta}{\text{Side adjacent to } \beta}$ (in triangle ABC) $= \dfrac{692}{1200} = .577$

2. .577 is the tangent of 30° (Table 10)

The angle of bank is 30°.

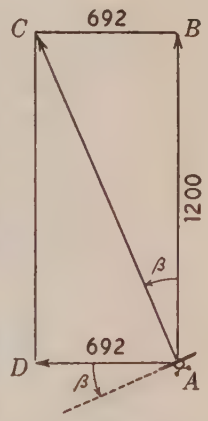


FIG. 143.

EXERCISE 4. What angle of bank is needed if a plane (*a*) weighs 1500 pounds and needs a centripetal force of 865 pounds? (*b*) weighs 1800 pounds and needs a centripetal force of 1500 pounds? (*c*) weighs 1100 pounds and needs a centripetal force of 1312 pounds?

PROBLEM 3. A plane is flying a circle at a 30-degree bank. It weighs 1200 pounds. What centripetal force is being exerted?

SOLUTION. (See Figure 143.)

1. $\dfrac{\text{Side opposite } \beta}{\text{Side adjacent to } \beta} = \tan 30° = .577$ (by table)

2. $\dfrac{CB}{1200} = .577$

3. $CB = .577 \times 1200 = 692$ pounds; the centripetal force is 692 pounds

EXERCISE 5. What centripetal force is being exerted by a plane —

(*a*) weighing 1200 pounds in a 50° bank?
(*b*) weighing 1500 pounds in a 50° bank?
(*c*) weighing 1800 pounds in a 70° bank?

EXERCISE 6. At what altitude must a plane fly an on-pylon turn in order to fly with a 1500-foot radius at 10°? at 20°? at 30°?

Two other trigonometric functions

The ratio of the side opposite an acute angle of a right triangle to the hypotenuse is called the *sine* of the angle. The ratio of the side adjacent to an acute angle of a right triangle to the hypotenuse is called the *cosine* of the angle. Tangents, sines, and cosines are called *trigonometric functions*.

If we let one of the acute angles of a right triangle be called θ (Greek letter Theta), as shown in Figure 144, and let the sides be designated a, b, and c, as shown, then —

$$\frac{a}{b} = \frac{\text{Side opposite } \theta}{\text{Side adjacent to } \theta} = \text{Tangent of } \theta \ (\tan \theta)$$

$$\frac{a}{c} = \frac{\text{Side opposite } \theta}{\text{Hypotenuse}} = \text{Sine of angle } \theta \ (\sin \theta)$$

$$\frac{b}{c} = \frac{\text{Side adjacent to } \theta}{\text{Hypotenuse}} = \text{Cosine of angle } \theta \ (\cos \theta)$$

PROBLEM 4. If a plane weighs 1200 pounds and is flying at a 30-degree angle of bank, what lift (*AC*, Fig. 143) is being required?

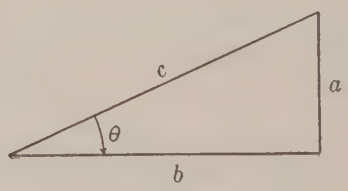


FIG. 144.

SOLUTION. 1. Angle $\beta = 30°$

2. $\dfrac{\text{Side adjacent to } \beta}{\text{Hypotenuse } \beta} = \text{Cosine of } 30° = .866$ (Table 11*b*)

3. $\dfrac{1200}{AC} = .866$

4. $1200 = .866 \times AC$

5. $AC = \dfrac{1200}{.866} = 1386$

A lift of 1386 pounds is being exerted.[1]

TABLE 11*b*

TABLE OF COSINES AND SINES

ANGLE	COSINE	SINE
10°	.985	.174
20°	.940	.342
30°	.866	.500
40°	.766	.643
50°	.643	.766
60°	.500	.866
70°	.342	.940
80°	.174	.985

EXERCISE 7. What is the lift necessary for —

(*a*) a 1400-pound plane at 40° angle of bank?
(*b*) a 1500-pound plane at 50° angle of bank?
(*c*) a 1700-pound plane at 60° angle of bank?

PROBLEM 5. A plane needs a centripetal force of 1259 pounds to fly a circle of given radius. The angle of bank is 40°. How much lift is needed?

[1] Note that in Step 3 of the solution we had an equation to solve in which the unknown (AC in this case) was in the denominator. Remember that if one number divided by the unknown equals a second number, the first number equals the second number times the unknown (Step 4), and the unknown equals the first number divided by the second number (Step 5). That is, if $\frac{a}{x} = b$, then $a = bx$ and $x = \frac{a}{b}$.

SOLUTION. (See Figure 143.)

1. $\frac{1259}{AC} = \frac{\text{Side opposite } \beta}{\text{Hypotenuse}} = \text{Sine of } \beta$
2. Angle $\beta = 40°$ Sin $40° = .643$
3. $\frac{1259}{AC} = .643$
4. $1259 = .643 \times AC$
5. $AC = \frac{1259}{.643} = 1958$

The lift needed is 1958 pounds.

EXERCISE 8. What lift would be needed

(*a*) if centripetal force is 1163 pounds and β is 50°?
(*b*) if centripetal force is 1299 pounds and β is 60°?
(*c*) if centripetal force is 1410 pounds and β is 70°?

Use of table of tangents, cosines, and sines

For solving problems in trigonometry you need a table of tangents, cosines, and sines for all the degrees — not just 10°, 20°, and so on, as in Tables 11 *a* and 11 *b*. Such a table is given on page 650. You should use that table hereafter in doing exercises.

Finding the height of a cloud bank

Figure 145 illustrates one method of finding the height of cloud bank at night. A searchlight at S shines straight up to the bottom of the cloud at C. By means of an instrument called a *clinometer* at a point P some distance from S, the angle SPC is read. From this angle and the distance PS the height CS of the cloud is found. The angle SPC is the *angle of elevation.*

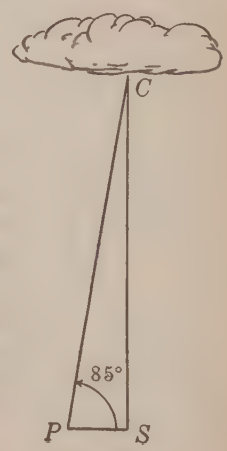


FIG. 145.

PROBLEM 6. If the light on a cloud is observed at a distance of 1000 feet from the searchlight and the angle of elevation is 85°, what is the height of the cloud?

SOLUTION.

1. $\frac{CS}{PS}$ = the tangent of angle P
2. The tangent of 85° is 11.43
3. $\frac{CS}{PS} = 11.43$
4. Hence
   $CS = 11.43 \times PS$
   $= 11.43 \times 1000$ feet
   $= 11{,}430$ feet

The height of the cloud is about 11,500 feet.

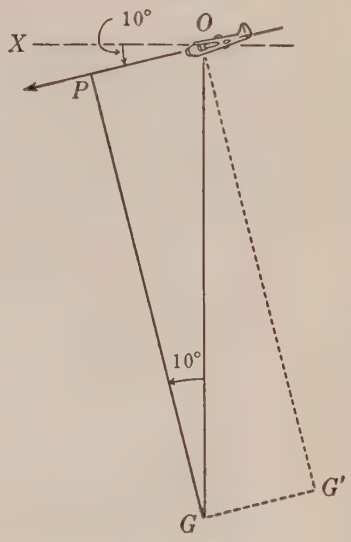


FIG. 146.

EXERCISE 9. What is the height of a cloud when the clinometer is 2000 feet from the searchlight and the angle of elevation is (*a*) 60°? (*b*) 70°? (*c*) 80°?

PROBLEM 7. What is the component of gravity which overcomes drag and propels a plane weighing 1200 pounds gliding at an angle of 10°?

SOLUTION. 1. Make a sketch as in Figure 146 to show how the gravity vector OG would be resolved graphically into two components, OP and OG', by the parallelogram law of forces.

2. Angle OGP = angle POX = 10°
3. Think: In right triangle OGP,

$$\frac{PO}{OG} = \frac{\text{Side opposite } 10^\circ}{\text{Hypotenuse}} = \text{sine } 10^\circ$$

4. The sine of 10° = .174
5. $\frac{PO}{OG} = .174$ $\quad PO = .174 \times OG$
   $= .174 \times 1200$
   $= 209$ pounds

The propelling component of gravity is 209 pounds. If you keep a notebook for your exercises, compare this answer with your first answer for Exercise 2 of Chapter 12.

EXERCISE 10. What is the component of gravity used in propulsion in Problem 7, when the angle of glide is 15°? Compare your answer with your second answer to Exercise 2 of Chapter 12.

EXERCISE 11. A boy flying a kite as shown in Figure 147 has let out 100 yards of string. He judges the angle of

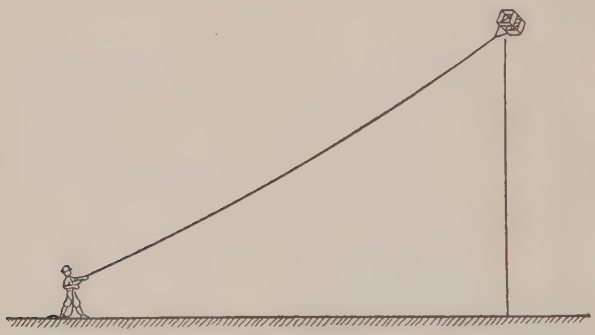


FIG. 147.

elevation of the kite to be 30°. If that is correct, how high is the kite and how far is the boy from the point directly below the kite? (Disregard the sagging of the string.)

EXERCISE 12. In Figure 148, $\frac{BC}{AC}$ is what function of angle A (sine, cosine, or tangent)?

$\frac{BC}{AB}$ is what function of angle A?

$\frac{AC}{AB}$ is what function of angle A?

EXERCISE 13. If a plane can climb 400 feet a minute while flying at 60 miles an hour, what is its climbing angle?

EXERCISE 14. If a plane can climb at 12°, what vertical distance can it climb in 10 minutes at 60 miles an hour?

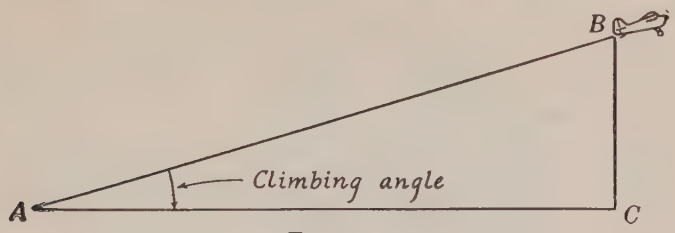


FIG. 148.

EXERCISE 15. In Figure 149, what ratio is the tangent of angle ABD? What ratio is the sine of angle ABD? What ratio is the cosine of that angle?

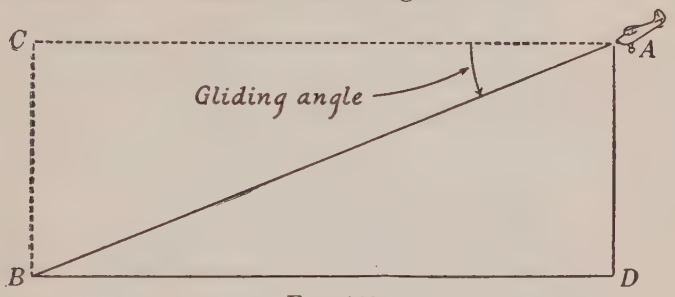


FIG. 149.

EXERCISE 16. The ratio $\frac{BC}{CA}$ is what function of angle CAB? Does angle CAB = angle ABD?

EXERCISE 17. If the gliding angle of an airplane is 6°, how far (BD in Figure 149) over the ground can it glide from an altitude of 1000 feet? (BD/AD = tangent of what angle?)

EXERCISE 18. If a glider can glide 1000 feet over the ground from an altitude of 70 feet, what is its gliding angle?

EXERCISE 19. In Figure 150, $\frac{\text{Nominal pitch}}{\text{Circumference}}$ is what function of the blade angle?

EXERCISE 20. The radius of the circle described by the nominal element of a propeller blade is 3 feet. What is the

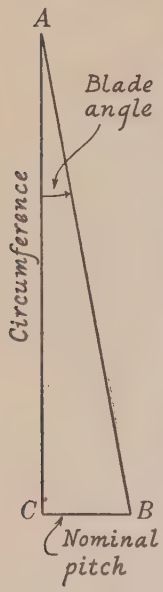


FIG. 150.

circumference of the circle described by this blade element when the propeller axle is stationary? (Circumference $= 2\pi r = 2 \times 3.14 \times$ radius.)

EXERCISE 21. If the circumference described by a nominal blade element is 18.84 feet and the nominal blade angle is 15°, what is the nominal pitch of the propeller?

EXERCISE 22. What circumference is described by the blade element that is 2 feet from the axis of rotation of the propeller?

EXERCISE 23. If the circumference described by a blade element is 12.56 feet and the nominal pitch is 5.05 feet, what is the blade angle of that element?

EXERCISE 24. An airplane is seen flying directly overhead at an estimated elevation of 5000 feet. Ten seconds later it is judged to be 15° from vertical. If these estimates are correct, what is the air speed of the plane?

EXERCISE 25. A bomber is flying at 150 miles an hour at 20,000 feet. A bomb dropped under those conditions will fall to the ground through a curve called the *trajectory*, and strike at a point P (Fig. 151) almost directly below point H where the plane is at the time the bomb strikes. Let us say it takes 36 seconds for the bomb to fall. What distance BH does the plane travel while the bomb falls? (One mile per hour = 1.467 feet per second.)

EXERCISE 26. At what *angle of depression* HBP must the target be sighted in order that the bomb will strike it?

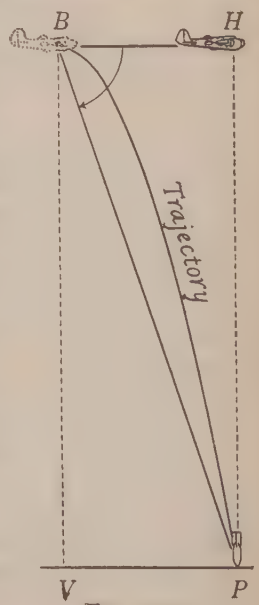


FIG. 151.

U. S. Navy Bureau of Aeronautics

'IG. 152. A 4-motored Navy atrol bomber, a flying boat, nanufactured by the Consoliated Aircraft Corporation. 'he function of this plane is to cout at great distances and to eport by radio the position of nemy vessels. It may be alled upon to do level bombng with bombs weighing a ton r more.

Trajectory

A bomb moves forward at the same speed as the plane,[1] as shown in Figure 151. Regardless of its forward motion the bomb falls about

16 feet in 1 second,
$2^2 \times 16$ feet in 2 seconds (64 feet),
$3^2 \times 16$ feet in 3 seconds (144 feet),
$4^2 \times 16$ feet in 4 seconds (256 feet),
$5^2 \times 16$ feet in 5 seconds (400 feet),
and so on.

The distance a body falls in a vacuum is expressed by the formula —

Distance fallen $= \frac{1}{2} g$ (time)^2, or

$S = \frac{1}{2} gt^2$ (Formula for the distance in feet through which a body falls in a given time)

in which —

S = the distance (span) in feet through which a body falls,
g = 32.2 and
t = the time in seconds during which the body falls.

[1] This is strictly true only in a vacuum. The resistance offered the *projectile* (bomb or other weight) slows its forward motion slightly and also makes the downward motion slower than what it would be in a vacuum.

EXERCISE 27. If a bomber is moving at 200 feet a second, how far forward does the bomb travel in 10 seconds? How far does it drop in 10 seconds? What is the angle of depression of the target at the point of release of the bomb if it strikes the target in 10 seconds?

EXERCISE 28. What is the angle of depression in Exercise 27 if the bomb is to strike the target in 20 seconds?

EXERCISE 29. A pilot is flying at an altitude of about $1\frac{1}{2}$ miles. He sees a town in the distance and judges the angle of depression of the town to be about 20°. If that is correct, how far is the town from the pilot horizontally?

EXERCISE 30. A pilot observes a cloud bank in the distance and judges the angle of elevation of the cloud base to be about 10°. What is the height of the cloud base (*a*) if the clouds are 10 miles away horizontally? (*b*) 15 miles away? (*c*) 20 miles away?

EXERCISE 31. A balloon is released at point *A* and its ascent timed. When the balloon is known to be 3000 feet up, its angle of elevation is 40°. How far has the balloon drifted horizontally from point *A* during its ascent?

EXERCISE 32. A glider pilot finds that from an altitude of 5000 feet he can glide to a point 18 miles away, horizontally. What is the gliding angle of his glider?

Summary of aerodynamics

Here are a few of the things you have learned about flying and airplane design in your study of aerodynamics.

1. Lift increases as angle of attack increases within limits, but not in exact proportion.

2. Drag also increases as angle of attack increases within limits, but not in proportion.

3. Wings of different shapes have somewhat different characteristics as to lift and drag.

4. The lift and drag of a wing vary directly in proportion to the area of the wing.

5. The lift and drag of a wing vary directly in proportion to the square of the velocity of the air (velocity of air over the wing or of the wing through the air).

6. The lift and drag of a wing vary directly in proportion to the density of the air.

7. The velocity with which a plane must fly in order that the lift created will sustain the weight of the plane varies —

(*a*) inversely as the square root of the wing area,

(*b*) inversely as the square root of the density, and

(*c*) directly as the square root of the weight.

8. The horsepower necessary to propel a wing at the velocity which it must have in order that the lift will sustain the weight of the plane varies —

(*a*) like the velocity, inversely as the square root of the wing area,

(*b*) like the velocity, inversely as the square root of the density, but

(*c*) directly as the weight multiplied by the square root of the weight ($W \times \sqrt{w}$ is sometimes written as $W^{\frac{3}{2}}$).

9. The available horsepower of an unsupercharged engine diminishes with altitude on account of reduction of oxygen per cubic foot.

10. Horsepower increases with revolutions per minute, within limits.

11. Some horsepower is lost by inefficiency of the propeller. That is, the amount of horsepower which goes to pull the plane is less than the horsepower the engine could exert on a load fastened to it. The greater the angle of attack of the propeller blades the less the propeller efficiency.

12. The greater the aspect ratio of a wing, the greater its aerodynamic efficiency.

13. The higher the temperature of the air, the less its density and the greater the minimum flying speed.

14. The greater the humidity, the less the air density and the greater the minimum flying speed.

Formulas

The following formulas have been presented:

1. Coefficient of lift

$$C_L = \frac{L}{\frac{\rho}{2} SV^2}$$

2. Lift

$$L = C_L \frac{\rho}{2} SV^2$$

3. Coefficient of drag

$$C_D = \frac{D}{\frac{\rho}{2} SV^2}$$

4. Drag

$$D = C_D \frac{\rho}{2} SV^2$$

5. Possible weight

$$W = C_L \frac{\rho}{2} SV^2$$

6. Required wing area

$$S = \frac{W}{C_L \frac{\rho}{2} V^2}$$

7. Required velocity

$$V = \sqrt{\frac{W}{C_L \frac{\rho}{2} S}}$$

8. Minimum flying speed (in feet per second)

$$\text{Min. } V = \sqrt{\frac{W}{\text{Max. } C_L \frac{\rho}{2} S}}$$

9. The drag of a flat plate

$$F = 1.28 \frac{\rho}{2} aV^2$$

10. Parasite drag

$$D_{par.} = 1.28 \frac{\rho}{2} aV^2$$

11. Total drag of a plane

$$D_{plane} = D_{wing} + D_{par.}$$

12. Thrust

$$T = C_D \frac{\rho}{2} SV^2$$

13. Thrust

$$T = D/L \times W$$

14. Power

$$H.P. = \frac{TV}{550}$$

15. Required horsepower

$$H.P. = \frac{(C_D \frac{\rho}{2} SV^2)V}{550}$$

16. Horsepower for a given weight

$$H.P. = \frac{(D/L \times W)V}{550}$$

17. Horsepower for the parasite

$$H.P._{par.} = \frac{1.28 \frac{\rho}{2} aV^3}{550}$$

18. Total horsepower

$$H.P._{plane} = H.P._{wing} + H.P._{par.}$$

19. Change of required air speed with density

$$A_n = \sqrt{\frac{\rho_o}{\rho_n}} A_o$$

20. Change of required horsepower with density

$$H.P._n = \sqrt{\frac{\rho_o}{\rho_n}} H.P._o$$

21. Change of required air speed with wing area

$$A_n = \sqrt{\frac{S_o}{S_n}} A_o$$

22. Change of required horsepower with wing area

$$H.P._n = \sqrt{\frac{S_o}{S_n}} H.P._o$$

23. Change of required air speed with weight

$$A_n = \sqrt{\frac{W_n}{W_o}} A_o$$

24. Change of required horsepower with weight

$$H.P._n = \frac{W_n}{W_o}\sqrt{\frac{W_n}{W_o}}\,H.P._o$$

25. Centripetal force needed for a turn

$$F_{centr.} = \frac{MV^2}{R}$$

26. Trigonometric functions

$$\text{Tangent } \theta = \frac{\text{Side opp. } \theta}{\text{Side adj. to } \theta}$$

$$\text{Sine } \theta = \frac{\text{Side opp. } \theta}{\text{Hypotenuse}}$$

$$\text{Cosine } \theta = \frac{\text{Side adj. to } \theta}{\text{Hypotenuse}}$$

27. Pivotal altitude

$$P.A. = .067\,A^2$$

28. A falling body

$$\text{Dist. fallen} = \tfrac{1}{2}\,gt^2$$

Questions

1. What is the tangent of an angle?
2. What is the cosine of an angle?
3. What is the sine of an angle?
4. How do you find the size of an angle when you know its tangent?
5. How do you find how much more lift is needed for a turn than for straight flight?
6. How do you find the lift necessary at a given angle of bank by the graphic method? by the trigonometric method?
7. What does the word "trigonometry" mean?
8. How is the height of a cloud sometimes found?
9. What is a clinometer?
10. What is an angle of elevation?
11. What is a trajectory?
12. What is an angle of depression?

20

TYPES OF AIRPLANES AND VARIATIONS

PLANES are of two general types in regard to wings — *biplanes*, having two wings one above another on each side, and *monoplanes*, having only one wing on a side.[1]

A few biplanes are still flown, but the tendency now is toward the use of monoplanes which avoid interference with air flow around one wing by air from the other wing.

Helicopter

A type of aircraft called a helicopter depends for support solely upon a powered rotor consisting of long, narrow blades revolving in a horizontal plane upon a vertical axis. (See Fig. 348, page 640.) ("Helicopter" means literally "spiral wing.") The helicopter has shown a good deal of promise, but it is yet in the experimental stage.

Autogiro

An autogiro may be thought of as an airplane that uses in place of wings, or in addition to small wings, a rotor similar to that of a helicopter but one that turns freely, self-propelled. (See Fig. 347, page 640.) ("Autogiro" means literally "self-revolving.")

A recent development in the autogiro is the "jump-off." At the beginning of a flight the rotor is joined to the engine and given excessive speed, first with the blades set to produce

[1] Technically a monoplane as shown in Figure 152 is considered to have only one wing. That is, the whole wing structure from one wing tip to the other is considered as constituting a single wing. In this sense a biplane has only two wings. Commonly, however, we speak of a monoplane as having "wings," one wing on each side.

The Soaring Society of America, Inc.

FIG. 153. Gliders in readiness for launching at Harris Hill, near Elmira, New York, during a recent Annual National Soaring Contest.

no lift. Then the engine is disconnected and the pitch of the blades (angle of attack) is increased and the autogiro caused thereby to "jump off." The autogiro then gets under way with the help of the propeller, while the rotor slows down to normal speed which it continues of itself.

Glider

A glider is an airplane without power — without propeller — of any kind. (See Fig. 153.) A glider has all the ordinary control surfaces, however (ailerons, rudder, elevators), and is maneuvered in the same way as an airplane in a glide. Some gliders have a landing gear that consists of a single wheel in the bottom of the fuselage protruding a portion of the wheel's diameter. Gliders are capable of gliding at a very slight angle, losing even as little as one foot of altitude to twenty feet of forward motion.

A glider may be launched like the stone of a slingshot — with rubber ropes pulled forward by manpower. Two men may hold the tail of the gliding plane while eight men stretch the rubber ropes. Then at a signal from the pilot the two men let go their hold and the plane shoots into the air, automatically dropping the ropes when well up.

Another way gliders are launched is by pulling with a cable which is wound on a drum by an engine as shown in Figure 154. When the glider has received sufficient height the pilot releases the cable, which drops to the ground.

Another method of launching gliders is by towing them to a sufficient height with a powered airplane.

Glider pilots take advantage of up-drafts of air, as on the windward side of hills and in some cloud formations, and thus they manage to stay up for many hours, traveling long distances. Gliders have soared as high as 18,000 feet in clouds, and they have "been carried" as far as 200 miles.

Seaplane

The term *seaplane* usually refers to a type of airplane similar to a land airplane, but without wheels and having two floats — one in place of each wheel. A float is a cigar-shaped airtight tank of light metal, or of rubber, upon which the plane rests in the water. (See Fig. 155.) Some types have a single float directly amidships below the fuselage. (See Fig. 156.)

The Soaring Society of America, Inc.

Fig. 154. Launching a glider. The cable is fastened to the nose of the glider in such a way that the pilot can pull a lever and drop the cable when sufficient altitude is reached.

Luscombe Airplane Corporation

FIG. 155. A seaplane with two floats. This is the most common type of seaplane.

A seaplane is taken off and landed into the wind very much as is a conventional land plane. It has the same controls and is maneuvered in much the same way as a land plane.

Seaplanes are usually wheeled to a ramp on a rolling platform, or beaching gear, and lowered into the water on the platform. They are returned to the hangar on the platform. However, some seaplanes, especially among navy seaplanes, have wheels, similar to those of an amphibian plane, on which they may roll into and out of the water; but these wheels are not strong enough to land on.

A seaplane used on salt water is usually hosed off thoroughly with fresh water after each use, in order to prevent any damage the salt water might do if left to dry on the plane.

Seaplanes operate only from relatively smooth water, and therefore usually from lakes, rivers, or protected harbors.

Pilots like planes that can operate from water because a land plane must usually be flown above 3000 feet for safety in picking out a landing place in an emergency, while a plane

U. S. Navy Bureau of Aeronautics

FIG. 156. A Vought observation-scouting plane used aboard battleships and cruisers. This is a mid-wing seaplane; it has a main float, and wing-tip floats to keep it from rolling over when on the water. Its function is principally to observe and report the position of the splashes of its mother ship's fire.

that can be operated from water is permitted to be flown 300 feet above the lake, river, or bay or calm sea over which it is operating, and this may be done without concern about landing places, since the plane can land safely at any time, so long as it is flying over calm water. (See also page 634.)

Flying boat

A second type of seaplane is called a *flying boat.* It has a hull in the form of a light boat, upon which it rests in the water. Mounted above the hull are the engine with its propeller, the wings, and the tail surfaces, whose functions are the same as in an ordinary airplane. (See Figs. 157 and 167.)

Either a seaplane or a flying boat can come down on land with reasonable safety to the pilot and passengers. The hull merely slides along the ground until the plane comes to rest, but of course this sliding may do some damage to the hull or floats.

Amphibian planes

A few planes, called *amphibians,* have been designed for taking off from and for landing on either land or water.

An amphibian is usually a flying boat with wheels so attached at the sides that they can be lowered when the plane is used on land or raised when the plane is used in the water. The wheels of an amphibian plane are made strong enough to sustain the shock of landing on them from the air.

U. S. Navy Bureau of Aeronautics

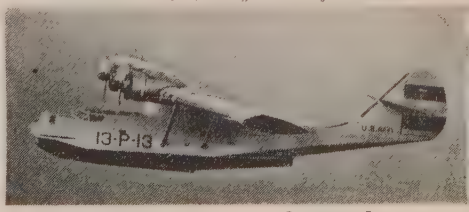


Fig. 157. A Consolidated bimotored Navy patrol bomber. This is a parasol-winged flying boat.

Tractor and pusher types

Airplanes are classified, also, as being of the *tractor* (puller) type, or of the *pusher* type, depending on whether the propeller is in front of the wing and "pulling" the plane or behind the wing and "pushing." Figure 159 shows a pusher-type plane.

Most planes are of the tractor or puller type, but small flying boats are often of the pusher type. In such flying boats the rear placement of the propeller makes for the convenience of the pilot when he reaches for the propeller — from within the plane which is on the water — to start the engine. A pusher-type plane is aerodynamically more efficient than a tractor type, but it is usually avoided on account of the necessity for a long propeller shaft.

Single-engine and multiple-engine types

Small planes ordinarily used by private pilots have only one engine and one propeller. Large planes of the passenger and bomber types have two, three, four, or more engines with a propeller for each.

A two-engine plane has less chance, of course, of both engines stopping at once than a single engine plane has of the one engine stopping.

Tail wheels and skids

As we have noted, some planes depend upon a mere skid — a backward projecting bar of metal — to support the tail

U. S. Army Air Corps

FIG. 158. A North American single-motored army observation plane. This is not a combat plane, but for defense it carries two fixed guns forward and a flexible gun aft.

Fig. 159. A bimotored army fighter plane designed to accompany long-range bombers. It is of pusher type, the propellers being mounted behind the trailing edge at the end of an extension shaft. The two gunners in front of the engine are kept free to fire their cannon forward.

U. S. Army Air Corps

of the plane on the ground. But the tendency is toward the use of a tail wheel, partly to prevent the tearing up of runways.

Tail wheels are of two general types — full-swivel and steerable.

A full-swivel tail wheel operates just like the caster wheel on a bedpost.

A steerable tail wheel is also swiveled; but the frame bearing the tail wheel is attached to the rudder by springs (see Fig. 160) or by rubber shock cord, so that the vertical axle rotates with the rudder. The rudder pedals are thus enabled to steer the tail wheel as well as the rudder.

In a stiff side wind a plane with a full-swivel tail wheel is difficult to manage, since the wind may blow the tail off to one side. In taxiing a plane with a full-swivel tail wheel the pilot must use the brake on the right wheel, for example, to counteract the push of the wind on the right side of the tail and thus keep the plane straight in taxiing.

Skill in applying just enough braking is difficult to acquire, and a pilot using a full-swivel tail wheel for the first time taxies "all over the place," trying to go straight ahead.

Sometimes a pilot cannot turn his plane downwind (say

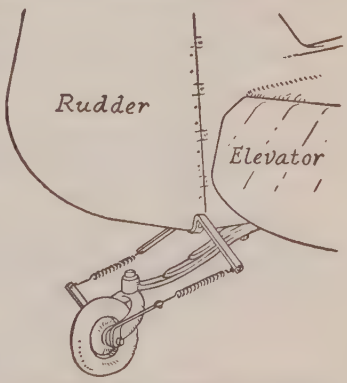


Fig. 160. A steerable tail wheel.

to the left with a strong wind on the right side of the tail). He has to turn upwind (to the right, in this case) to get up momentum for a strong swing on around to downwind, before the wind can stop him on the other side.

Taxiing such a plane puts a lot of wear on the brakes.

A plane with a steerable tail wheel can be taxied with comparative ease in a crosswind if the plane is not of too great weight. A steerable tail wheel is not suitable for use on a heavy plane because the rudder pedals would be unmanageable on account of the great force needed to turn the rudder.

Airliners use full-swivel tail wheels partly in order to turn in a small circle (relative to the size of the plane); this can be done easily because the airliner has a propeller on each side of the fuselage. To turn left, the pilot gives the right engine power while the left engine idles, at the same time applying the left brake.

High-lift devices

Many airplanes have wing loadings so great that their normal landing speed is greater than would be safe at all times. These planes therefore make use of what are called *high-lift devices*. High-lift devices are of two types, *flaps* and *slots*. Both are means for increasing the lift coefficient of a wing.

Flaps

A flap is essentially a device to give a wing more camber at the trailing edge. The simplest flap is a hinged portion of the rear edge of the wing, very much like an aileron, which may be lowered to make a bend in the wing, as shown in Figure 161.

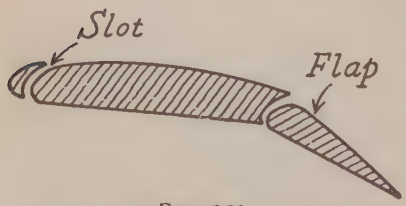
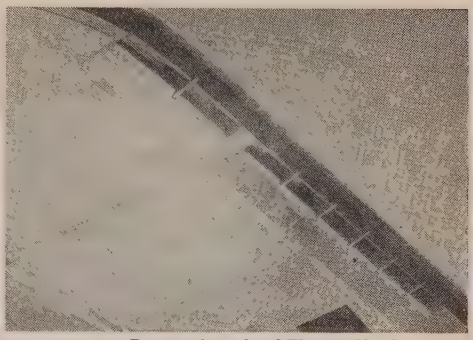


Fig. 161.

FIG. 162. A flap on the wing of a Boeing Stratoliner.



Transcontinental and Western Air, Inc.

FIG. 163. A slot in the wing of a transport plane (see below).

The flap of a wing is between the aileron and the fuselage, or may even extend across below the fuselage from aileron to aileron. Ailerons move in opposite directions, but both flaps move down together.

When flaps are extended, a wing has a higher lift coefficient. This enables the plane to obtain necessary lift at a lesser velocity. The flaps are lowered when about to land and the plane is enabled to land at 60 miles an hour perhaps, whereas otherwise 70 or 80 miles an hour might be required.

Slots

A slot is essentially a device to cause the air to flow more smoothly over the upper surface of a wing at a high angle of attack and thus reduce or prevent burbling. Figure 161 shows a common type of slot placed near the leading edge of the wing. A slot may be placed anywhere along the chord of a wing; some wings are provided with two or more slots.

By preventing burble, the slot enables the plane to fly at a higher angle of attack without stalling and in this way get more lift. This also helps to reduce the speed necessary for landing.

Slots provided principally for slowing landing speed usually extend the length of the wing or nearly so. Such

slots are often movable and may be either automatic or controllable by the pilot. Other slots are fixed.

Other planes are provided with fixed slots near the wing tips only, which serve principally to prevent wing-tip stalling and maintain aileron control at slow speeds.

Variable-pitch propellers

When the blades of a propeller are set at the most efficient blade angle for cruising, they are not at the best blade angle either for climbing or for speeding. For example, when a plane is put into a climb, more load is put on the engine. The *RPM* is consequently somewhat reduced, hence efficiency is lost. Moreover, the forward motion of the plane is slowed relative to the rate of turning of the propeller and consequently the efficient angle of attack of the blades is lost.

To overcome these difficulties in a climb, it is necessary that the blades be set at a lesser blade angle. This reduction of blade angle is somewhat analogous to low gear in an automobile. It permits the propeller to resume its efficient *RPM* and efficient angle of attack.

In view of this need for changing the blade angle of a propeller while in flight, propellers have been devised with blades, the blade angle of which can be adjusted by the pilot to suit the degree of climb. These are called *variable-pitch propellers.*

Variable-pitch propellers have been found helpful also in increasing propeller efficiency in high speed as well as in climbing. In such a case the blades are adjusted so as to have a greater blade angle instead of a lesser one.

Constant-speed propellers

The most efficient propeller is one that turns at a constant speed in revolutions per minute, with the angle of attack at

all times adjusted to the various speeds at which the plane flies. Hence means are provided for adjusting the angle of attack of the propeller blades automatically. When the load is light and the propeller would otherwise race, the angle of attack is increased. When the load is heavy, as in a climb, the angle of attack of the propeller is decreased. By this arrangement the speed of the propeller is kept constant.

Full-feathering propellers

There are times when one engine of a multi-engined plane may stop and as the plane continues to fly with the remaining engines the air forces the propeller of the dead engine to *windmill*. The resistance of the windmilling propeller causes excessive drag and the windmilling may cause further damage to the engine.

In order to avoid these difficulties some propellers are now capable of being turned so as to present the leading edge to the relative wind when not rotating, thus eliminating all windmilling tendency and reducing drag to a minimum. This is called *feathering* the propeller.

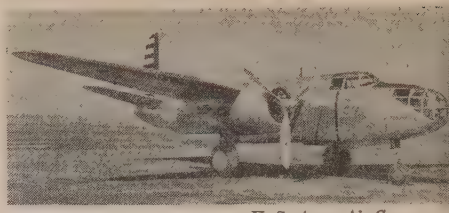
Reverse-pitch propellers

The development of variable-pitch propellers has been carried even to the point of enabling propellers to be turned so that the pitch is reversed and they then force the air forward instead of backward. A propeller reversed in this manner acts as a brake, the same as the propeller of a ferry-boat which is turned backward as the boat approaches the dock. Also, if a large flying boat has two propellers and one is reversed, the plane can be turned on a small radius.

Tricycle landing gear

Various airplanes are constructed with what is known as a tricycle landing gear, as shown in Figures 164, 165, and

U. S. Army Air Corps



U. S. Army Air Corps

FIGS. 164 and 165. Two of the very fastest existing bombers: The Martin (left) and the Douglas. Both these planes are bimotored, high-winged, equipped with tricycle landing gear.

91. In these planes two landing wheels are placed behind the center of gravity, instead of in front of it as in conventional planes; the customary tail wheel or skid is omitted; and there is a single nose wheel placed ahead of the two main landing wheels.

The plane when on the ground rests on the three wheels in an attitude approximately the same as for flying. The two main wheels, side by side, are fixed in direction, but the nose wheel is given *caster action* (like the wheel on a bedpost caster).

Advantages claimed for the tricycle landing gear are:

1. Greater passenger comfort when on the ground. Some of the large passenger planes are equipped with tricycle landing gear. Conventional-type passenger planes slant down very decidedly when resting on the ground and are then consequently uncomfortable for seated passengers.
2. Better vision. This applies particularly to light planes. In most conventional light planes the pilot cannot see over the nose when taxiing and must lean first to one side, then to the other, and even turn the plane a little, in order to see where he is going. With tricycle landing gear, the pilot in a light plane can see over the nose in taxiing the same as in flying.
3. No tendency to nose over. A conventional plane will sometimes nose over — tip up the tail and strike the

nose on the ground, damaging the propeller — when the wheels strike a rut or the brakes are put on too suddenly. The nose wheel tends to prevent this.

4. Shorter landing run. This is because the brakes can be applied more promptly and more strongly when there is no danger of nosing over. Also the brakes are more effective — the plane has better traction — because it is taxiing with the wings at a lower angle of attack, thus having less lift.
5. The plane is less likely to be blown over in a strong wind when on the ground facing the wind. This is because of the lesser angle of attack of the wings.

One disadvantage of the tricycle landing gear is found when the caster-acting nose wheel "shimmies." ("Shimmying" means oscillating or wagging violently from side to side. But shimmying also occurs with tail wheels and can be corrected in design.)

A nose wheel does not ride over obstacles as well as a tail wheel.

Retractable landing gear

Passenger planes and military planes flying overhead appear smooth underneath, as their landing wheels do not project like those of light planes. This is because the landing wheels have been retracted (drawn up) inside the fuselage or wings — at least most of the way.

The object of the retracting landing gear is to eliminate, as far as possible, drag caused by the resistance of the wheels to the free flow of air past the fuselage.

In passenger planes it is customary to permit the landing wheels to project somewhat, say about one third. For one thing, there is not room in the wings to enclose the landing wheels conveniently and completely. Further, in the case of a forced landing it is desirable to land with the wheels thus projecting part way. They then sustain the

shock of landing but permit the fuselage to slide along the ground without excessive damage except to propellers.

Stratoliners

The stratosphere, about which you will learn more in a later chapter, begins at about 35,000 feet altitude and extends to the upper limit of the atmosphere. All of the turbulence and storm activity of the atmosphere occurs below the stratosphere. There are high winds in the stratosphere, but these are steady and no menace to flying.

It has been a dream of airmen that eventually it would be possible to fly in the stratosphere, or at least high enough to avoid a large part of the turbulence and storm activity occurring at moderate altitudes. The term *stratoliner* was coined to refer to airliners that might be capable of flying in the stratosphere, but the term now refers merely to high-flying passenger planes.

Flight in the actual stratosphere is still considered rather impractical; but it has been found that flying even at altitudes between 16,000 and 20,000 feet is high enough to avoid most turbulence and storms. Passengers cannot be carried comfortably, breathing the air at the diminished pressures prevailing at such altitudes; and stratoliners are now equipped with what are called *pressure cabins*, in which, by supercharging, air pressures corresponding to those at lower altitudes are maintained. It is considered that the air pressure at an altitude of 8000 feet, rather than that at sea level, is an optimum pressure to be maintained in airplane cabins. (See Fig. 166.)

In the pressure-cabin planes, or stratoliners, now operated by the Transcontinental and Western Air on the transcontinental runs from New York to Chicago, Kansas City, Alburquerque, and Los Angeles, the altitudes flown are between 16,000 and 20,000 feet. At the 8000-foot level the supercharging of the cabin begins; that is, fresh air from

outside the cabin is forced into the cabin by the engine in such a way as to maintain the atmospheric pressure at 8000 feet, even though the plane rises higher. Stale air is forced out from the bottom of the fuselage, while a supply of fresh air continues to be blown in by the supercharger.

Between the altitudes of 8000 and 15,000 feet a stratoliner's "cabin altitude" is kept at 8000 feet; but at altitudes between 15,000 and 20,000 feet the pressure of the air in the sealed cabin is allowed to decrease slightly until a maximum "cabin altitude" of 12,000 feet is reached, which is recognized as the upper altitude limit for passenger comfort.

At an altitude of 15,000 feet the air in the sealed cabin, which is at 8000-foot pressure, exerts a pressure of $2\frac{1}{2}$ pounds per square inch on the inside of the walls of the cabin. It requires a considerable additional structural weight to withstand even this pressure of air inside the cabin, and it is not considered feasible to allow the inside pressure to exceed

FIG. 166. The interior of a Stratoliner under construction. Scale is indicated by the height of the two air hostesses. Note that the fuselage has a circular cross section to allow the cabin to be pressurized. The circular members are called "bulkheads" and the small longitudinal members are called "longerons" or "stringers."

Transcontinental and Western Air, Inc.

the outside pressure by more than $2\frac{1}{2}$ pounds per square inch. That is why the inside pressure is allowed to diminish above the altitude of 15,000 feet. It has been found possible to fly up as high as 30,000 feet or even up to 36,000 feet; and while flight at such altitudes would avoid practically all turbulence and clouds, it is not considered practical for ordinary air transports to do so. It is obvious that much time and power are required to reach these high altitudes in the first place; and hence it is feasible to attain them only in flights of about a thousand miles or more. Moreover, the higher the altitude the greater the strength of the cabin must be in order to withstand the extra pressure of the air within. This additional weight of construction reduces the pay load. Also, of course, the higher the altitude the greater the distance for the plane to ascend and to descend, and of course climbing takes more time than level flight.

There are disadvantages in high-altitude flying; but there is one advantage which comes from the fact that the less dense the air is, the greater is the possible speed. Moreover, wind velocity as high as 100 miles an hour has been found to exist in very high altitudes; and when it is possible to take advantage of such wind velocity a great deal of time is saved. Experiments have shown that even in flying through the clouds at high altitudes, there is less menace to safety on account of icing on the wings than at low altitudes. This is because of the fact that the temperatures range from 10 to 50 degrees below zero, and even though moisture is encountered it forms on the wings only as small ice crystals of the kind popularly called "hoarfrost." These crystals immediately fly off the wings and do not pile up like icing at lower altitudes, which is so dangerous to aviation.

Experts believe that it will be possible in the future to develop pressure-cabin planes suitable for flying at altitudes as high as 25,000 feet.

The Clipper

The modern Clipper ships as used by the Pan-American Airways Company in its transatlantic air-transportation service, are Boeing flying boats, the largest commercial aircraft in the world. They are powered with four engines of 1550 horsepower each totaling 6200 H.P. They have a wing span of 152 feet and an overall length of 106 feet. Their cruising speed is about 160 miles an hour and their high speed about 190 miles an hour. The fuel capacity of a Clipper is 5460 gallons, giving the plane a cruising range of 4800 miles. A Clipper weighs 84,400 pounds (over 42 tons); it can climb 800 feet a minute at sea level and 100 feet a minute at 15,000 feet (service ceiling). (See Fig. 167.)

The engines are mounted in nacelles on the wings. The wings are large enough to allow members of the crew to pass through them to the engine while in flight. Each engine drives a three-blade, 14 foot 9 inch, constant-speed propeller which automatically adjusts its blades to put an even load on the engine regardless of the speed or altitude of the Clipper.

Each transatlantic Clipper is equipped with an automatic pilot (described in Chapter 39), although two pilots are at the controls at all times during flight. In fact, a plane of the size of the Clipper requires a crew of eleven. All take-offs and landings are made by a pilot himself, but during level flight the automatic pilot is used.

Pan-American Airways System

FIG. 167. A Yankee Clipper, a flying boat on a return trip from Europe, headed for La Guardia Field, New York. The nose is painted black to reduce glare from the sun in the pilot's eyes.

Questions

1. How do monoplanes and biplanes differ?
2. What is a helicopter? What is an autogiro?
3. What is a glider?
4. What is a seaplane? What is a flying boat?
5. What terms distinguish between an airplane with the propeller in front of the engine and one with the propeller behind the engine?
6. Why does a plane sometimes have more than one engine?
7. What varieties of tail support can you name?
8. Can you describe two kinds of tail wheels?
9. How does the steerable tail wheel operate? What advantage has it over the full-swivel tail wheel?
10. What is an amphibian plane?
11. What is meant by the term "variable-pitch propeller"?
12. What advantage does a variable-pitch propeller have over a fixed-pitch propeller?
13. What is meant by a constant-speed propeller?
14. What is meant by feathering a propeller? When is a propeller feathered?
15. What might be gained by a passenger plane's flying in the stratosphere?
16. What disadvantage is there in flying at 16,000 to 20,000 feet altitude?
17. What is the reason that "stratoliners" do not provide air at sea-level pressure for passengers in the cabins?
18. The pressure of what altitude is provided in a stratoliner?
19. Why do passenger planes fly at high altitudes only on long non-stop trips?
20. How fast does the wind sometimes blow at high altitudes? Is this likely to be an advantage or a disadvantage?
21. What is a tricycle landing gear?
22. What advantages are claimed for it?
23. What is retractable landing gear? What are its advantages?
24. What are flaps, their purpose and method of operation?
25. What are slots, their purpose and method of operation?

PART III

Avigation

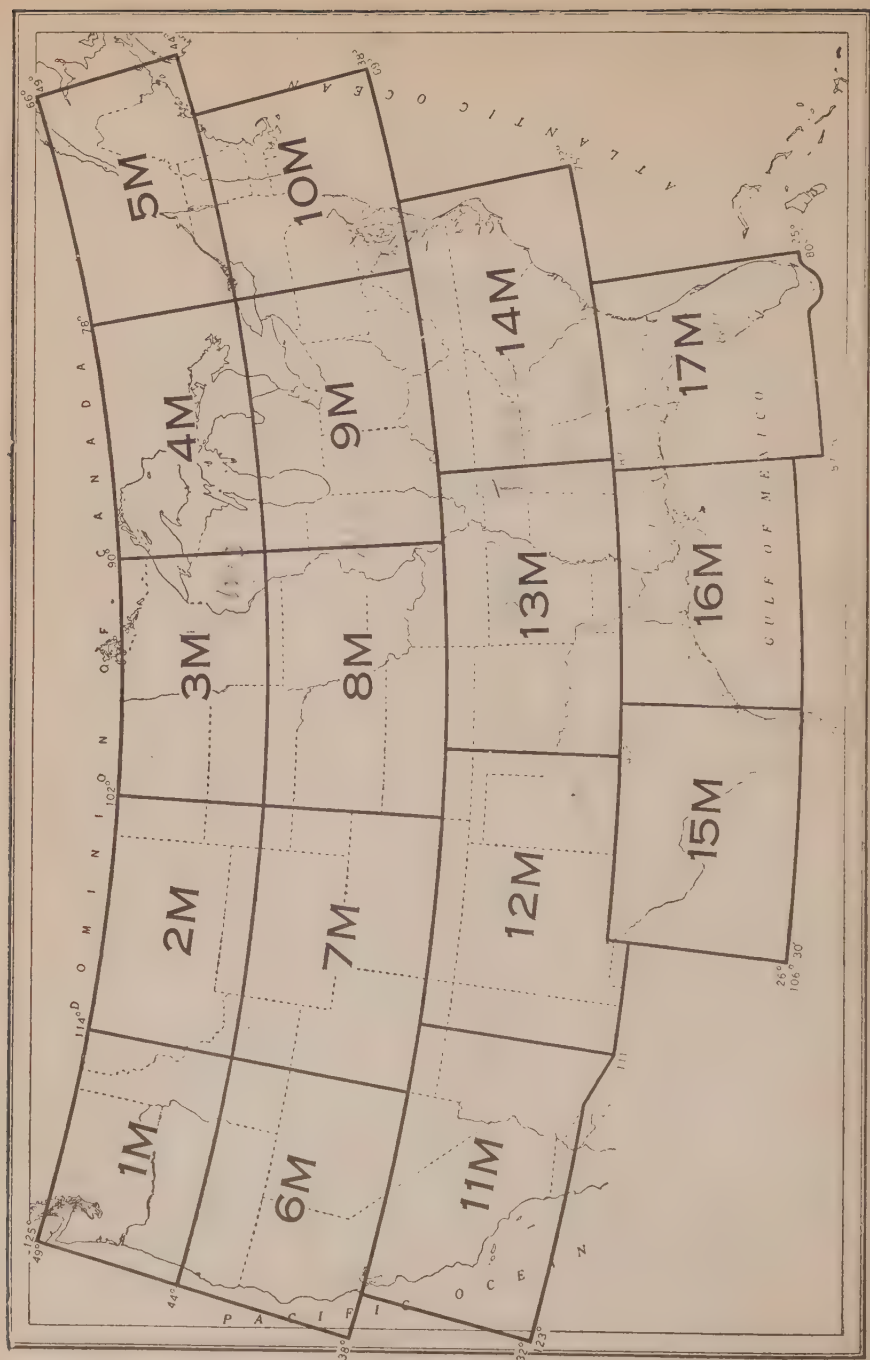


FIG. 168. Index to the regional charts.

21

AERONAUTICAL CHARTS

"NAVIGATION" means the science or art of conducting a vessel on the water. This includes the determination — from landmarks, where there are any, and from principles of geometry and astronomy — of the vessel's position on the globe, its course, and the distance traversed. The word "navigation" is based on two Latin words — *navis*, a ship; and *agere*, to go. For what we might call aerial navigation a new term has been coined: "avigation," based on the Latin word *avis*, meaning bird, and *agere*, to go — literally, "bird going." "Avigation" applies to conducting any aircraft — a dirigible as well as to an airplane. However, usage sanctions the expression "aerial navigation."

Need for charts

While it is *desirable* to have a road map when motoring, to identify roads and keep one's directions, it is *essential* to have a chart (map) when flying — unless one is flying along a river or is otherwise safely guided by known landmarks.

The United States Coast and Geodetic Survey publishes a variety of maps especially designed for pilots. Among these are two series of charts of special value:

Regional charts covering the United States in 17 sheets, at a scale of 1/1,000,000, or about 16 miles to the inch, and

Sectional charts covering the United States in 87 sheets, at a scale of 1/500,000, or about 8 miles to the inch.

Figure 168 shows the areas covered by the various regional

FIG. 169. Index to the sectional charts.

charts, and Figure 169 shows the areas covered by the various sectional charts.

Each sectional chart is named for a prominent city, usually located near the center of the chart. The size of the charts is about 2 feet by 4 feet. They may be bought at many airports or from the Civil Aeronautics Authority at Washington, D. C.

A sectional chart shows the following details, among others:

Cities and towns, showing approximate size.
Railroads, showing single and double track.
Highways, main and secondary.
Transmission lines (electric).
Rivers, lakes, and coast lines.
State boundaries.
Airports, beacons, seaplane bases, etc.
Radio ranges.
Special landmarks — oil-well derricks, race tracks, lookout towers, lava beds, etc.
Mountains, peaks, ranges, hills.
Contours — lines of equal elevation.
Meridians of longitude and parallels of latitude.
Directions measured from north by degrees.
Scales of miles.
Civil airways.
Isogonic lines (see page 303).
Contiguous charts.

Symbols representing these features are explained on the margin of the chart. Each chart is dated.

The regional charts are the more convenient when you are planning a long trip, and, as a rule, when you wish to find the bearing of one point from another when the two points are not on the same sectional chart. But for reference to landmarks when flying by pilotage, the sectional charts are more convenient.

Fig. 170. Elevations represented by contours.

Contours

A contour line (or merely contour) is a line on the map showing points of the same elevation. If we thought of the ocean as being, say, 10,000 feet higher than at present and drew lines to mark the water's edge, or the coast lines, around all the mountains, then let the water sink to 9000 feet and drew another set of lines marking the new coast-lines, then did the same for 8000 feet, 7000 feet, and so on, we should have the contours shown on the charts.

The manner in which contours indicate the nature of a terrain is shown in Figures 170 and 171. The use of differ-

Fig. 171. The hills shown in Figure 170 by contours.

ent colors in the sectional charts — darker brown for higher elevations — makes the mountain ranges stand out clearly.

How an aeronautical chart is drawn

The Coast and Geodetic Sectional and Regional Charts are drawn according to a system known as the *Lambert conformal conic projection.* The system was invented by a famous mathematician, Johann Heinrich Lambert, about 1750.

In connection with charts and maps, the term *projection* means any representation of any portion of the earth's surface on a flat surface.

Conformal representation

The type of chart used in avigation is said to be *conformal* because a specific area (such as a square or circle) on the earth's surface is represented on the chart with a shape that very closely conforms to the shape of the actual area. (You understand, of course, that it is not possible to flatten out a piece of a hollow rubber ball without some stretching or squeezing or both, and for a similar reason it is not possible to represent any area of the earth's surface on a flat surface with all measurements in true proportion.)

The chart is said to be in *conic* projection because it is drawn as if done first on a portion of the surface of a cone and then flattened out.

Thus at (*a*) in Figure 172 we see a ring of the earth's surface bounded by two parallels,[1] *H* and *K*.

At (*b*) we see the same ring of the earth's surface represented on a portion of a cone. It has the shape of a lamp shade. The circles representing parallels *H* and *K* are the

[1] *Parallels* are imaginary circles on the earth's surface parallel to the equator and to each other.

Meridians are imaginary semicircles on the earth's surface extending from pole to pole.

same as at (*a*), but the meridians *MP*, *NO*, and the like are now straight lines.

At (*c*) we see portion *MNOP* of the ring shown at (*a*); and at (*d*) the same area is represented on a portion of a cone but is flattened out. In the representation at (*d*) the "parallels" are now concentric circles; and the meridians

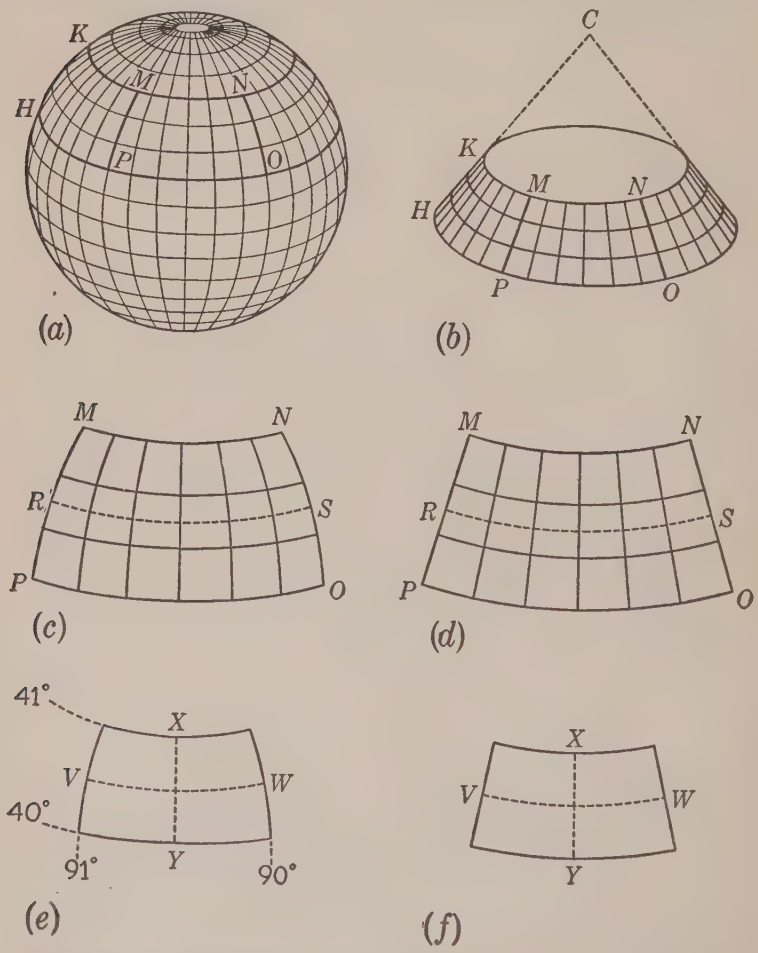


FIG. 172. The projection of meridians and parallels upon a cone.

are straight lines, all of which converge to a point which was the apex *C* of the cone.

You will understand that in straightening the lines *MP* and *NO* we shorten the length of arc *RS*; that is, we distort the shapes of areas on the surface. What is an approximate square on the earth's surface becomes squeezed sidewise into an approximate rectangle higher than it is wide.

In drawing the chart, the cartographer must correct this fault. To do so he first draws the meridians and then adjusts the spacing of the arcs on the chart representing the parallels of latitude in such a way that a given area on the earth retains its shape on the chart as nearly as possible. For example, in representing on the chart the area on the earth's surface bounded by the parallels of 40° and 41° and by the meridians of 90° and 91°, shown exaggerated at (*e*) in Figure 172, the cartographer uses a distance *XY* on the chart such that the ratio of the height *XY* to the average width *VW* (at (*f*)) is the same as the ratio of the height *XY* of the corresponding area (at (*e*)) on the earth's surface to its average width, *VW*.

This means that on any one chart the same scale of miles can be used vertically that is used horizontally, with approximate accuracy; and the same scale can be used for any other direction — distortion of shapes has been reduced to a minimum.[1]

It means also that a line on a chart drawn at 45° to some meridian represents a line on the earth's surface also at 45° with that same meridian; and it is the same way for any other angle. Hence the chart can be used with accuracy sufficient for all practical purposes in finding the true direction of any point from any other point.

[1] For charts covering the northern and southern parts of the country the scale of miles necessarily differs slightly from the scales for charts covering the central part — about 7.8 miles to the inch in the Miami chart, as against about 7.95 miles to the inch in the Washington chart; but each chart is measured in accordance with its own scale of miles, hence this difference is of no particular consequence.

Methods of avigation

The methods of avigation may be grouped under four general heads: *piloting*, *dead reckoning*, *radio avigation*, and *celestial avigation*.

Piloting, as a general term, means merely steering a vessel or flying an airplane. The term *piloting* has been used technically, however, to denote the kind of navigating one does in getting to one's destination with the help of a chart or map by following a highway, railroad, transmission line, river, or other such course; or by flying from one landmark to another which can be seen, as flying first to a mountain, then to a lake which can be seen from the mountain, then to a city which can be seen from the lake, and so on.

Piloting as a method of keeping track of one's position and of getting to one's destination hardly needs comment as a science. It is like finding one's way by map while motoring. Hints and suggestions regarding the art of piloting are given in the chapter on cross-country flying.

Dead reckoning refers to the technique of flying by chart and compass. The term is believed to be derived from the expression "deduced reckoning" which was contracted to "ded" reckoning. Dead reckoning (discussed in Chapters 22 and 23) involves finding the distance and direction of one's destination, the necessary *heading* (direction of pointing the plane), and the finding of one's position on the earth from time to time while on the course through consideration of the course flown and the elapsed time.

Radio avigation (discussed in Chapter 28) refers to the use of radio in getting to one's destination.

Celestial avigation refers to the science and art of conducting an aircraft by the observation of celestial bodies — sun, moon, and stars. The principles are the same as for the navigation of a vessel on the high seas, and they are not discussed in this text.

Questions

1. What is navigation? avigation?
2. What are the regional charts?
3. What are the sectional charts?
4. Who prepares the regional and sectional charts?
5. What does a sectional map show? Name as many things as you can.
6. What are contours?
7. The regional and sectional charts are called Lambert conformal conic projections. Who was Lambert?
8. Why are these charts called conic projections?
9. Why are they called conformal?
10. How are the charts made so as to be conformal?
11. What is piloting?
12. What is dead reckoning?
13. What is radio avigation?
14. What is celestial avigation?

22

DEAD RECKONING

DEAD reckoning, as explained earlier, refers to the finding of distance and of direction to one's destination by means of charts and directing the plane by means of the compass. It involves finding the necessary heading (pointing) of the plane to allow for wind drift, and finding a *fix* whenever necessary. Finding a *fix* means orienting oneself — finding one's position, from which a distance and direction may be measured.

Computing distances by a chart

If it is desired to find the distance between two towns, *A* and *B*, on a chart, mark the distance between *A* and *B* on the edge of a card, as shown in Figure 173; then place the card along the scale of miles, as shown, and read the distance in miles. In the figure the distance *AB* is 48 miles.

EXERCISE 1. On the Exercise Chart, Figure 174, find the distance (*a*) from Alfa to Berg; (*b*) from Berg to Cape; (*c*) from Cape to Alfa.

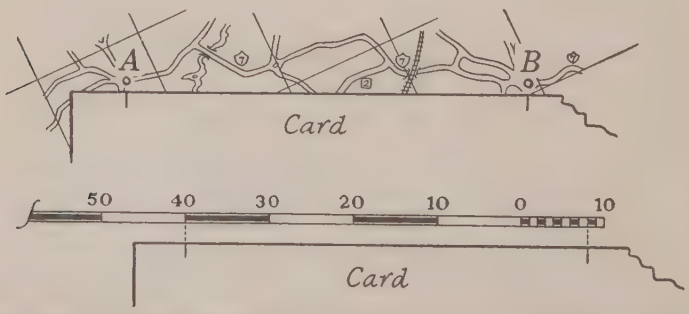


FIG. 173. Use of the scale of miles for measuring distances on a chart.

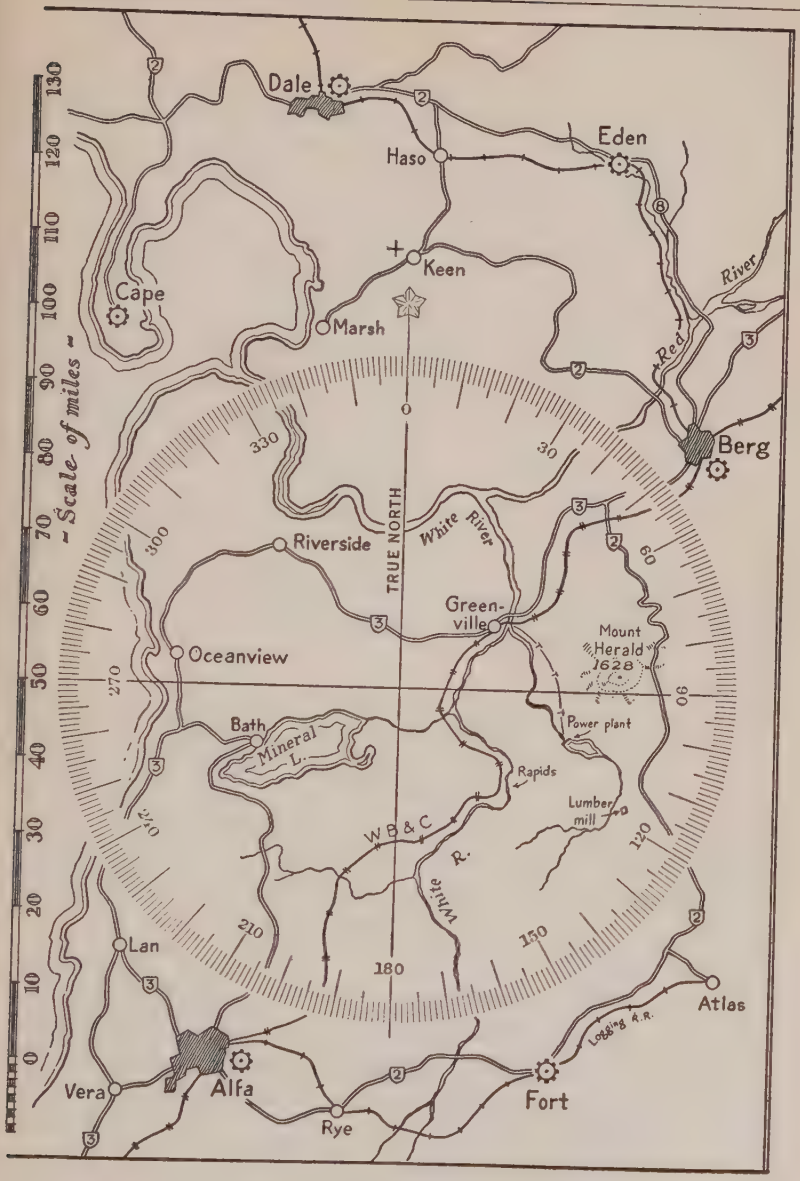


FIG. 174. Exercise chart.

Measuring direction

The direction of a point B from a point A (when the points are only a few miles apart) is found by drawing a line on the chart from A to B, extending this to cross the nearest meridian, and finding the angle the line makes with the meridian.

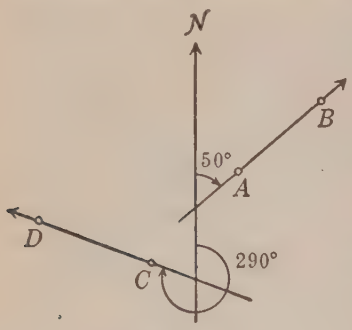


FIG. 175.

The direction of a line is expressed in terms of the angle it makes with north, as indicated by the meridian, the angle being measured clockwise. Thus the direction AB in Figure 175 is 50° and the direction CD is 290°.

The angle of direction so found on the chart agrees very closely with the true angle on the earth's surface — close enough for all ordinary avigational purposes.

Compass rose

In several places on each sectional and regional chart there is printed in red a large circle divided into degrees, as shown in Figure 176. Such a graduated circle is called a *compass rose.* The vertical line, marked zero, points to the same point toward which the "meridians" of the chart converge, and hence represents true north for that location.

Finding a bearing

The direction of one point B on the earth's surface (or chart) from another point A is said to be the *bearing* of B from A. To find the approximate bearing of a point B from a point A on a chart, we may use the compass rose, as shown in Figure 177. The steps are as follows, when A and B are not far apart:

(1) Draw a line on the chart through A and B.

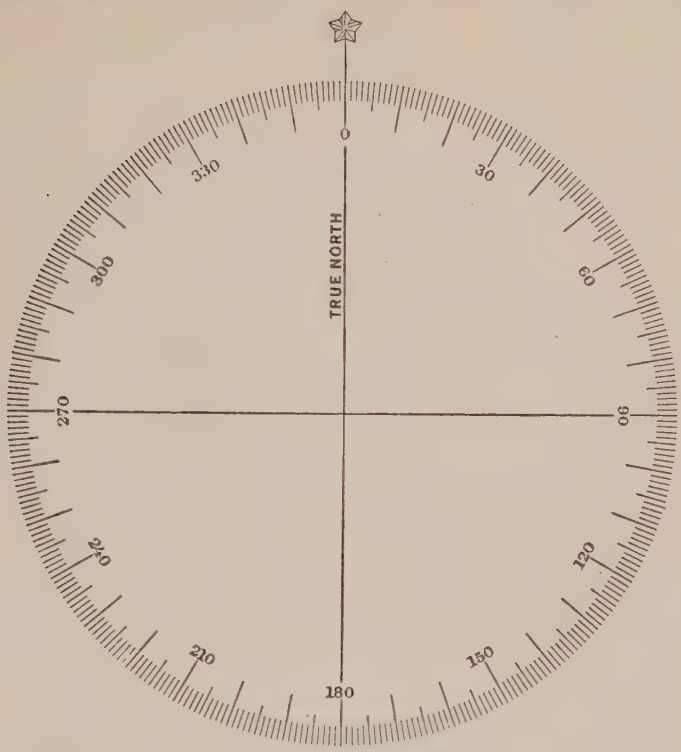


FIG. 176. A true compass rose.

(2) Draw a line (XY) through the center of the compass rose parallel to line AB. (This may be done with a straight-edge and triangle, as shown in Figure 177.)

(3) Read the scale where XY intersects it. This is very close to the true bearing if A and B are not over 100 miles apart. The bearing of B from A in Figure 177 is about 40°.

EXERCISE 2. Find the bearing (a) of Berg from Alfa; (b) of Cape from Berg; (c) of Alfa from Cape.

True course

Strictly speaking, the bearing of a point B from a point A is the angle (a) the line AB makes with the meridian directly

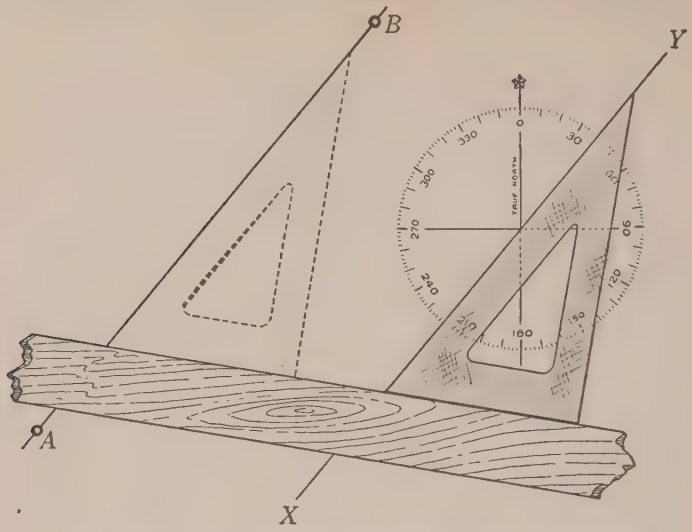


FIG. 177. Use of the compass rose in finding bearings.

through A, as shown in Figure 178. The bearing of A from B is the angle (b) which the line BA makes with the meridian through B. Angle b' does not equal angle a because the meridians are not parallel.

If you were to set out to fly from A to B, always maintaining a direction of flight represented by angle a from north, you would not pass directly over B but would veer slightly to the north of it, as shown in an exaggerated manner in Figure 179. To establish a constant heading by which to fly from A to B, therefore, it is customary, when A and B are a considerable distance apart, to measure the angle (c) that line AB makes with a meridian halfway between A and B in Figure 178. This is called the *true course* from A

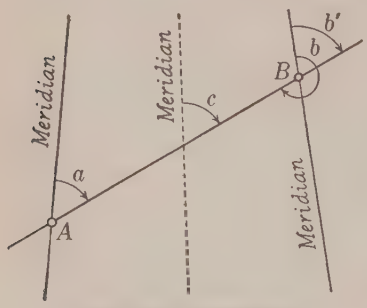


FIG. 178. Bearings.

to B. The *true* course is distinguished from the *magnetic* course, for example, which we shall consider later.

EXERCISE 3. Obtain the sectional map that includes your locality. Choose three airports, A, B, and C, some distance apart. Find the distance and true course (*a*) from A to B; (*b*) from B to C; (*c*) from C to A.

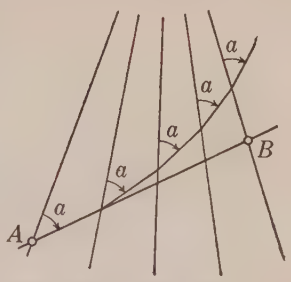


Fig. 179. The path of an airplane following a constant bearing.

Magnetic north

In Figure 175 the direction or bearing of B from A is indicated as 50°, the angle that AB makes with *true* north. A compass needle ordinarily does not point to true north but points to magnetic north. A compass tends to point toward a point on the earth's surface called the *north magnetic pole.*

The north magnetic pole is not at the north pole but is at a point on the edge of North America, above Hudson Bay, at latitude 71° N. and longitude 96° W., as shown in Figure 180. On the 96th meridian the compass points approximately north, but to the west of the 96th meridian the compass tends to point east of north, and to the east of the meridian the compass tends to point west of north, as shown by the arrows in Figure 180.

Variation

The number of degrees by which a compass needle points away from the true north pole at any locality is called the *magnetic variation* at that locality. Thus, if a compass indicates north when the needle (or plane) is pointing 2° west of north, the variation is said to be 2° west.

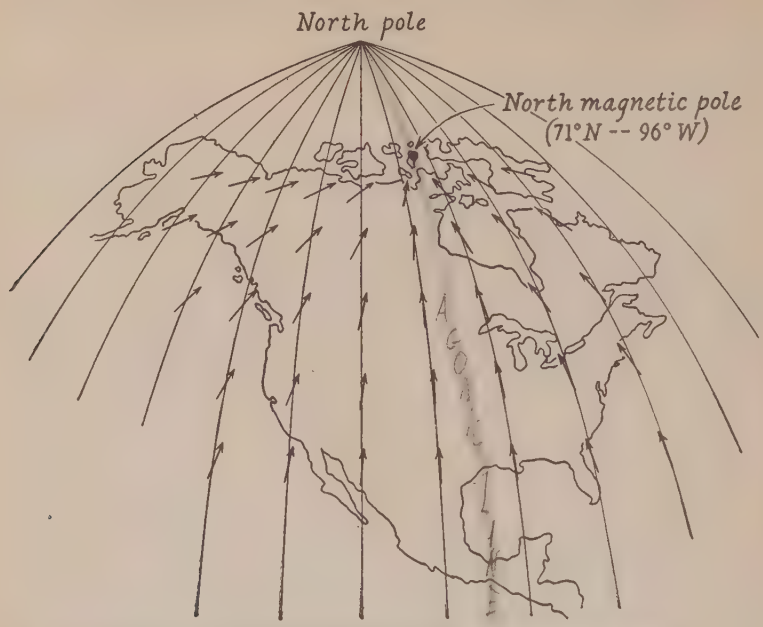


FIG. 180. The magnetic pole and magnetic variation.

Isogonic lines

A line through all points having the same variation is called an *isogonic line.* (*Iso* means equal; *isogonic* means having equal angles.) Figure 181 shows various isogonic lines. We note, for example, that along the upper Mississippi the variation is approximately 5° east; that is, in these localities the compass points 5° east of north. For some reason the 0° isogonic line does not follow the 96° meridian as we would expect, but slants off to the southeast. The other isogonic lines also are irregular.

Isogonic lines for each degree of variation east and west are shown as red dotted lines, on the U. S. Coast and Geodetic Survey Charts.

EXERCISE 4. Find the approximate magnetic variation at each of the three airports chosen in Exercise 3.

Magnetic course

When the direction of a line *AB* is measured from true north, we speak of the course *AB* as a *true course.* This really means that we have a true measure of the direction *AB*. But when the direction of the line *AB* is measured from magnetic north, we speak of the course *AB* as a *magnetic course.* The direction of the line *AB* is the same in both cases, but the measures are different because of being made from different starting points.

The magnetic course *AB* is the direction indicated by an accurate compass in a plane flying from *A* to *B* with no cross wind. "Finding a magnetic course" means finding the reading to which the compass of a plane would need to be held in order to fly from *A* to *B*, assuming no cross wind and presuming the compass to point to magnetic north at all times. (Conditions which prevent a compass from always pointing to magnetic north are discussed later.)

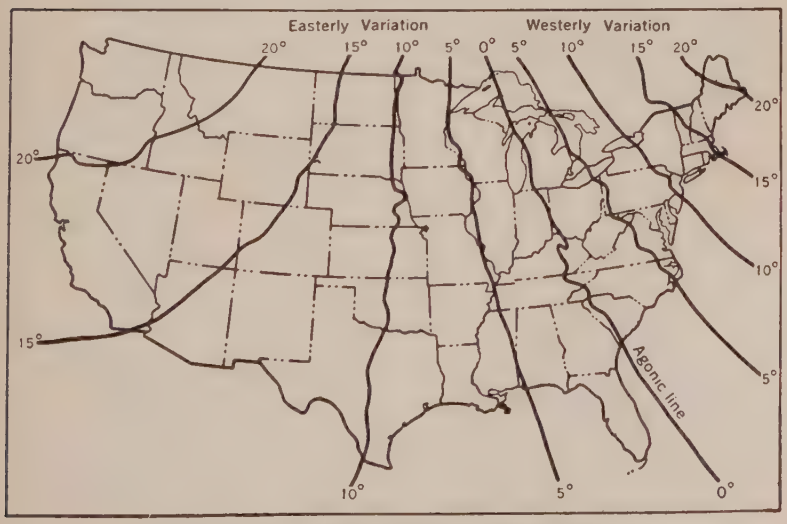


FIG. 181. Isogonic lines in the United States.

Let us say we are planning to fly in a direction northeast (45°) from Columbus, Ohio. The isogonic line through Columbus is marked 2° W., showing that the compass points 2° west of north at Columbus.

If the course is indicated by line *OD* at (*a*) in Figure 182 (*ON* being true north) but an accurate compass indicates magnetic north in the direction of *OM*, 2° west of north, then by the compass the course *OD* is indicated as 47° (east of north). We say, therefore, that the magnetic course *OD* is 47°.

You will remember that "east of north" really means *clockwise from north*, for if the true course is, say, 270°, as shown at (*b*) in Figure 182, the expression "270° east of north" might be slightly confusing.

Finding the magnetic course

We see from Figure 182 that if in a given instance we know the true course that we wish to fly and know the amount of the variation in that locality, we may find the magnetic course by one of the following procedures:

(*a*) If the variation is west, add the variation to the true course.

(*b*) If the variation is east, subtract the variation from the true course.

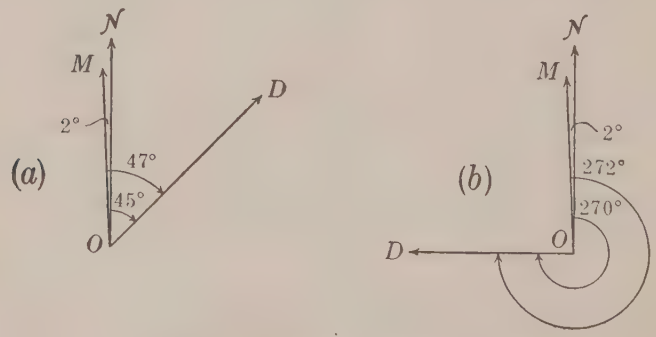


FIG. 182. Finding a magnetic course.

If the true course is 45° and the variation is 2° W., the magnetic course is 45° + 2°, or 47°.

If the true course is 45° and the variation is 2° E., the magnetic course is 45° − 2°, or 43°.

EXERCISE 5. Assuming the variations to be 5° W. in the Exercise Chart, page 297, find the magnetic course (*a*) from Alfa to Berg, (*b*) from Berg to Cape, (*c*) from Cape to Alfa.

EXERCISE 6. Find the magnetic course from *A* to *B*; *A* to *C*; and *B* to *C* (the three airports you chose in Exercise 3).

Finding the true course from the magnetic course

There are occasions in which a pilot may know the magnetic course and wish to find the true course. To do so he uses one of the following procedures:

(*c*) If the variation is west, subtract the variation from the magnetic course.

(*d*) If the variation is east, add the variation to the magnetic course.

EXERCISE 7. The magnetic course from *D* to *E* is 285°. The variation is 5° E. What is the true course from *D* to *E*?

"Add west to true"

Many devices have been proposed for remembering whether to add or subtract the variation. It seems simplest, however, merely to remember these four words: Add west to true.

This means that if the variation is west and the correction for variation is being made to the *true course* to get the magnetic course, you should *add* the variation.

You will then understand that if the variation is east, it is subtracted from a true course to get a magnetic course, and so on.

All you need to remember is, Add west to true; then you will know that you should —

(1) Add west variation to the true course to get the magnetic course.

(2) Subtract east variation from the true course.

(3) Add east variation to the magnetic course.

(4) Subtract west variation from the magnetic course to get the true course.

Correction of compass errors

The needle of a compass is a magnet and the engine in the plane is mostly iron (steel). As a magnet attracts iron, so iron attracts a magnet; and thus the engine attracts the nearest end of the compass needle, deflecting the needle. If you are flying toward the northeast, let us say, the engine is northeast of the compass and the north-seeking end of the needle will be turned slightly to the east, causing an error in the compass reading. Other airplane parts containing iron add other errors.

Deviation

It is possible to eliminate these compass errors in part by auxiliary magnets set near the compass needle, but some errors will still persist. The error of a compass reading owing to magnetic attractions in the plane is called *deviation*.

The *variation* of the compass reading is the same for all directions, but the amount of *deviation* necessarily differs with the different directions in which the plane will point. Hence it is customary to place a card or chart in the cockpit near the compass, indicating the amount of deviation for various magnetic headings.

Deviation card

The accompanying typical *deviation card* shows, for example, that when the plane has a magnetic heading of

Magnetic Heading	0	30	60	90	120	150
Deviation	0	4 W.	5 W.	0	4 E.	3 E.
Magnetic Heading	180	210	240	270	300	330
Deviation	1 W.	4 W.	5 W.	0	6 E.	5 E.

DEVIATION CARD

30° it has a deviation of 4° west; that when it has a magnetic heading of 60° it has a deviation of 5° west, and so on. Intermediate values in this case would be found by *interpolation.* That is, since at 90° the deviation is 0° and at 120° it is 4° east, at 105° (halfway between) the deviation is taken as 2° east, halfway between 0° and 4°.

Deviation chart

Figure 183 shows a typical deviation chart. From a chart of this kind it is possible to obtain the deviation for any given magnetic course without interpolation. Thus, we see that for a magnetic course of 10° the deviation is between 1° and 2° west; for 20°, about 3° west; etc.

EXERCISE 8. According to the Deviation Chart, what is the deviation for magnetic course of (*a*) 30°? (*b*) 50°? (*c*) 150°?

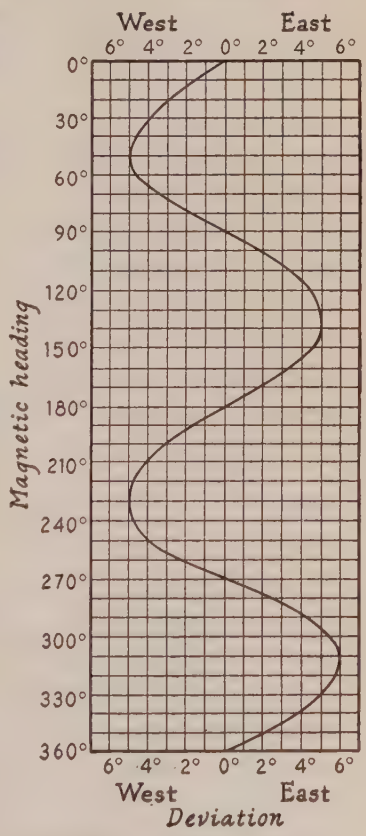


FIG. 183. A typical deviation chart.

Compass course

When a magnetic course has been altered to allow for the deviation of the compass, the course is then called the *compass course.* Thus, if to fly in a given direction you have to head the plane so that your compass reads 5°, we say that your compass course is 5°.

Finding the compass course

If we know the magnetic course in a given instance and wish to find the compass course, we may do so by one or the other of the following procedures:

(*e*) If the deviation is west, add the deviation to the magnetic course.

(*f*) If the deviation is east, subtract the deviation from the magnetic course.

If the magnetic course is 47° and the deviation is 3° W., the compass course is 47° + 3°, or 50°.

If the magnetic course is 47° and the deviation is 3° E., the compass course is 47° − 3°, or 44°.

EXERCISE 9. A magnetic course is 204°. What is the corresponding compass course if the deviation of the compass is (*a*) 3° W.? (*b*) 4° E.?

Finding the magnetic course from the compass course

There are occasions in which a pilot may know the compass course and the deviation and wish to find the magnetic course. To do so he will use one of the following procedures:

(*g*) If the deviation is west, subtract the deviation from the compass course.

(*h*) If the deviation is east, add the deviation to the compass course.

It is possible to make use of the expression *Add west to true* to help us remember the four procedures (*e*), (*f*), (*g*),

and (*h*). We need only remember that the compass course is subject to the error of deviation and hence of the two courses the magnetic may be considered as more nearly the true course. That is, if we think of the magnetic course as the *truer* course in this case and think of our expression as meaning in this case "Add west to truer," this will help us remember that to find the compass course from the magnetic course we add west deviation. From that we can remember all four procedures, (*e*), (*f*), (*g*), and (*h*).

EXERCISE 10. A compass course is 69°. What is the corresponding magnetic course if the deviation of the compass is (*a*) 4° W.? (*b*) 5° E.?

Finding the compass course from the true course, and vice versa

In avigation it is usually necessary to correct for both variation and deviation together. That is, the pilot presumably wants either to find the compass course from the true course, or the true course from the compass course. In either case it is customary to use the following procedure:

1. Make five columns as shown.

T	*V*	*M*	*D*	*C*

2. Head these, *T V M D C*, as shown, to stand for True, Variation, Magnetic, Deviation, and Compass. (To remember the order of these letters, some pilots have memorized this: "The Variation Makes Daily Changes"—which is true; it changes very slightly.)

3. Then, in going toward the right (starting with *true*), add west variation and west deviation (subtract east).

4. In going toward the left, add east variation and east deviation (subtract west).

PROBLEM 1. Let us say a pilot has the following data and wishes to find the compass course:

(*a*) True course 114°
(*b*) Variation 6° west
(*c*) Deviation as in Figure 183

What is the compass course?

SOLUTION. 1. Draw the diagram — *T V M D C*.

T	*V*	*M*	*D*	*C*
114	6 W.	120	4 E.	116

2. Enter the true course 114° under *T* and the variation 6 W. under *V*.

3. Add 6° west variation to 114°. This gives magnetic course 120°.

4. Find the deviation for 120° from the figure. It is 4° E. Enter it.

5. Subtract 4° east deviation. This gives the compass course 116°.

PROBLEM 2. Let us say a pilot has been steering a compass course of 200°. What is the true course if the variation is 8° E. and the deviation is as in Figure 183?

SOLUTION. 1. Draw the diagram.

T	*V*	*M*	*D*	*C*
205	8 E.	197	3 W.	200

2. Enter the compass course under *C*.

3. Find the deviation (3 W.). Enter it.[1]

4. Subtract west deviation, going to the left (200 − 3 = 197, magnetic course).

5. Add east variation (197 + 8 = 205°, true course).

[1] Strictly speaking, the deviations in the deviation chart are for magnetic courses, but when you wish to find the deviation corresponding to a compass course it is sufficiently accurate to assume the deviations to be for compass courses.

If you always write the letters *T V M D C* in this order, you may prefer to remember this expression: "Add west, going to the right," instead of "Add west to true."

EXERCISE 11. Using the Deviation Chart, find the compass course (*a*) from Alfa to Berg, (*b*) from Berg to Cape, (*c*) from Cape to Alfa. (Variation, 5° W.)

EXERCISE 12. Using the Deviation Chart and the three airports you chose on the sectional chart, find the compass course (*a*) from *A* to *B*; (*b*) from *B* to *C*; (*c*) from *C* to *A*.

EXERCISE 13. In the following cases, what is the true course from *D* to *E*? Use the Deviation Chart.

(*a*) compass course 100°, variation 4 W.;
(*b*) compass course 230°, variation 6 E.;
(*c*) compass course 310°, variation 5 W.

QUESTIONS

1. What is a fix?
2. How would you find the distance between two airports from a sectional chart?
3. What is a compass rose?
4. What is meant by the bearing of one airport from another?
5. How would you find a bearing?
6. What is meant by the true course from one airport to another?
7. Why is the bearing of *B* from *A* not the true course from *A* to *B*?
8. What is a true course?
9. What is the north magnetic pole?
10. What is magnetic variation?
11. What is a magnetic course?
12. What are isogonic lines?
13. How would you find the magnetic variation at a given airport?
14. How do you find a magnetic course from a true course?
15. What is meant by the expression "Add west to true"?
16. What is meant by deviation?
17. What is the compass course?
18. How do you find the compass course from the true course?

23

WIND DRIFT

SUPPOSE we undertake to fly from A to B, as shown in Figure 184. We point the plane in the direction AB and fly for one hour. In calm air we would arrive at B, 100 miles from A, in just an hour, let us say.

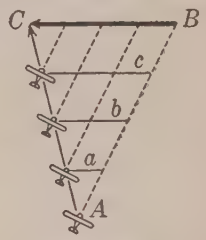


FIG. 184.

But suppose the wind is blowing in the direction BC with such velocity that a balloon which was at B at our starting time would drift to C in just an hour.

During the first quarter hour our plane would drift the distance a; during the first half hour the plane would drift the distance b; and so on. At the end of the hour the plane would be at C.

It was pointed in the direction of AB all the time, but it has flown the path AC over the ground.

Projected air path

The line AB shows the path from the starting point which the plane would have taken if the air had not moved. Let us call this the *projected air path* of the plane.

Heading

The direction AB, in which the plane was pointed during the trip from A to C, is called the *heading* of the plane.

Track

The line AC shows the path the plane actually took over the ground. It is called the *track* of the plane.

Course

A line of any length from A drawn in the direction AC is called the *course* of the plane. The course differs from the track merely in that a course is generally thought of as indicating merely the direction and position of a track — not its length.

Wind vector

The line CB shows the direction of the wind and the distance the wind blew in one hour. CB is called the *wind vector* for one hour. If we call a line a wind vector and do not mention the time, it is understood to be for one hour.

Drift angle

The angle BAC is called the *drift angle* of the plane. The drift angle of a plane is the angle between the heading and the course or track. If the course is to the left of the heading, as in this case, the drift angle is said to be to the left. If the course is to the right of the heading (looking from the starting point), the drift angle is said to be to the right.

Crabbing

You will see that in flying from A to C the plane moves with a partly sidewise motion. This kind of motion is called *crabbing.*

Skidding is partially sideward motion with reference to the air. Drifting, or crabbing in ordinary flight, is straight-ahead motion with reference to the air. It is sideward motion only with reference to the earth.

Trail of a plane

If the plane that traveled from A to C, as shown in Figure 184, had emitted a series of puffs of smoke while going from A to C, at the end of the hour these puffs of

smoke would have appeared as shown by the line *DC* in Figure 185. The initial puff of smoke drifted from *A* to *D* during the hour and each later puff of smoke drifted a lesser distance. The puffs lie in a straight line.

Let us call *DC* the *trail* of the plane as it flew from *A* to *C*.

The trail shows the heading

The trail of a plane is always in the same direction as the projected air path. (The two lines are parallel.) Hence, of course, the direction of the trail is also the heading. The plane is always pointing in the direction of its trail.

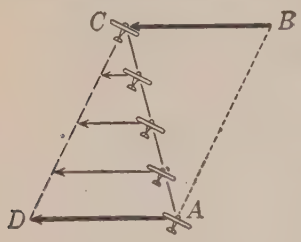


FIG. 185.

In Figure 185, *AD* is also the wind vector. That is, *AD* is the same length as *BC* and runs in the same direction.

Air-path drifts

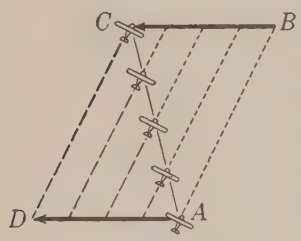


FIG. 186.

At any time between the starting time and ending time of the trip we may think of the air path of the plane as partly trail and partly projected air path, as shown in Figure 186. Figure 186 shows how the air path starts at *AB* and drifts to *DC* during the hour.

Time designation of trail

It is sometimes convenient to mention the time at which the trail of a plane is in a given position. Thus we might say that the trail in its first position shown in Figure 186 is the trail *as of* one-quarter hour after the starting time; that the trail in the next position shown in the figure is the trail *as of* one-half hour after the starting time, etc.

Air speed

As you learned in Chapter 4, the speed of the plane in its path through the air (AB or DC) is called the *air speed* of the plane.

The air speed is usually expressed in miles per hour. The projected air path of a plane for a one-hour flight is equal in length to the air speed; and, also, the trail of a plane for a one-hour flight is equal in length to the air speed.

Ground speed

The speed of the plane in its movement over the ground (along the track) is called its *ground speed.* The ground speed, like the air speed, is usually expressed in miles per hour. The ground speed may be greater than the air speed (as in the case of a partial *tail wind*) or equal to the air speed or less than the air speed (as in the case of a partial *head wind*).

Since we call AD or BC the wind vector, we might call AB or DC the *propeller vector.* If we could let the wind blow the plane in the direction AD for an hour as if attached to a balloon, and then let the propeller carry the plane in still air in the direction DC for an hour, the plane would be at C, of course. The propeller vector is often called the *air-speed vector.*

Similarly, if we let the propeller carry the plane from A in still air for an hour (to B) and then let the wind drift the plane (like a balloon) for an hour, the plane would also arrive at C.

If both the wind and the propeller move the plane for an hour, the plane goes from A to C in an hour.

Adding vectors

Finding the direction and distance AC (Fig. 185), having given AB and BC or having given AD and DC, is called

adding vectors. The line AC which is found is called the sum of the vectors or the *resultant vector.*

Solving wind-drift triangles

Triangle ABC is called a *wind-drift triangle,* and so is triangle ADC. A wind-drift triangle has a track for one side, a wind vector for another side, and an air path for the third side. The air path may be the projected air path (AB) or the trail (DC).

In avigation we often know some parts of a wind triangle and need to find the other parts. That is called *solving a wind-drift triangle.* For example, we might know the projected air path AB and the wind vector BC and want to find the track AC. Or we might know the track AC and the wind vector and want to find the heading, and so on.

Velocity

We often find it convenient to use a single word to mean both speed and direction. The word "velocity" is sometimes used to mean speed and direction, and let us use it with that meaning in discussing wind triangles.

Wind direction

In indicating the direction of a wind it is customary to state the direction *from* which the wind is blowing. That is, a south wind is a wind blowing from the south, hence blowing toward the north. A 90° wind is a wind from 90° (east) and hence blowing in the direction of 270° (west).

Finding the track

If we know the projected air path and the wind velocity (speed and direction) and want to find the track, we usually draw AB, then BC, and then AC. This is called solving a triangle when you know the lengths of two sides and their directions.

Finding the wind vector

If we know the projected air path (AB) and the track (AC) and want to find the wind vector, we usually draw AB and AC (either one first), then BC. This again is solving a triangle when you know the lengths and directions of two sides.

Finding the heading

Let us say that we know the course (direction of the track), the wind velocity (speed and direction), and the air speed, and that we wish to find the heading. We need to solve a triangle when we know the length and direction of one side and the directions but not the lengths of the other two sides. This makes the procedure a little different from that of the preceding paragraphs, as shown below.

Drawing to scale

In solving wind-drift problems we need to draw lines carefully to scale. Thus, if we want to represent miles on a sheet of paper, we may let one sixteenth of an inch represent a mile, or let one millimeter represent a mile, or let one inch represent 10 miles.

For scale drawing it is most convenient to have a decimal scale such as a metric rule or a rule with inches divided into tenths. In Figure 187, if a millimeter represents a mile, the

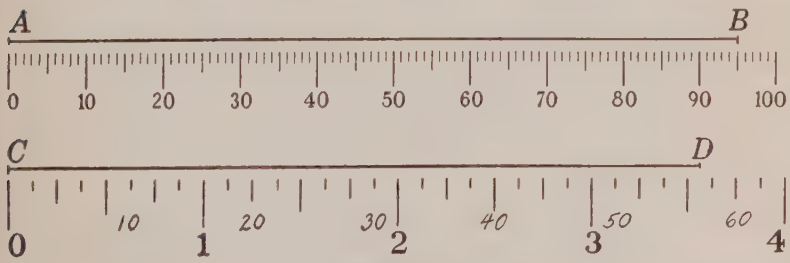


FIG. 187.

line AB represents 95 miles. Or a millimeter may represent 2 miles, in which case AB represents 190 miles.

If you do not have a decimal scale, it is well to write 10, 20, 30, and so on, on the scale you use, as shown at the bottom in Figure 187. In this case one-eighth inch represents 2 miles; so the line CD represents 57 miles. If necessary you could let one-eighth inch represents 3 miles.

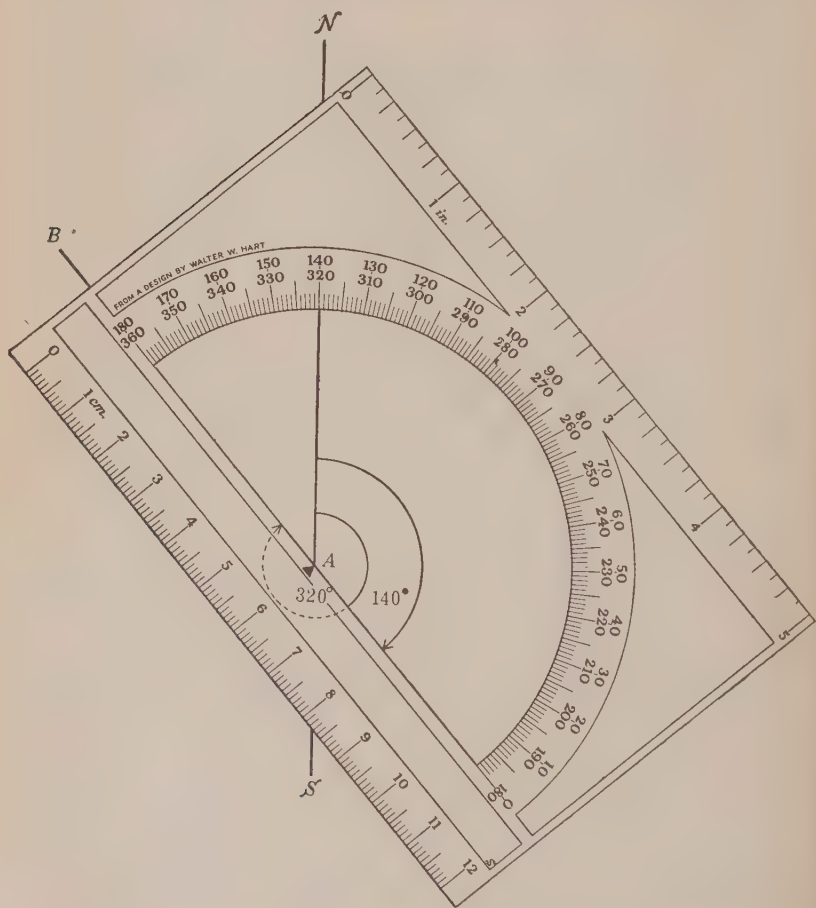


FIG. 188. An angle measured with a protractor.

Protractor

Also you will need a *protractor* for measuring angles, as shown in Figure 188. In the figure the angle NAB is being measured (clockwise) and found to equal 320°.

Protractor and scale

A combined protractor and scale is furnished with this book. See inside back cover.

Finding the course and ground speed

The course and ground speed of a plane are represented by the track for one hour. Problem 1 shows how we find the course and ground speed when we know the wind velocity and the projected air path (that is, the heading and the air speed).

PROBLEM 1. Let us suppose that a plane is heading in the direction 25° with an air speed of 90 miles an hour, as shown by vector AX in Figure 189, and that the wind is known to be blowing from 140° at 30 miles an hour, as shown by vector AW. What is the course and what is the ground speed?

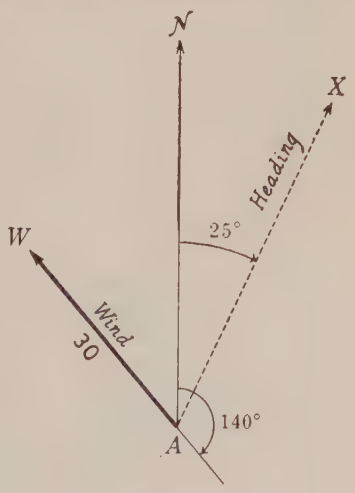


FIG. 189.

SOLUTION. 1. From any point A draw a line AN to represent north (Fig. 190).

2. With the help of a protractor draw a line AX to represent the heading (making an angle of 25° with AN).

3. Using some convenient scale, lay off on AX a distance AB to represent the projected air path (90 miles).

4. From B draw BN' to represent north.

5. From B draw a line BY in the direction in which the wind is blowing (from 140° as shown).

6. On BY lay off the wind vector BC (representing 30 miles motion of the air).

7. Draw AC. The vector AC represents the track of the plane.

8. Measure angle NAC to find the course. It is about 11° in this figure.

9. Measure vector AC to find the ground speed. It is about 107 units long in this case; hence the ground speed is about 107 miles an hour.

Method

In a problem of finding the track of a plane (course and ground speed), it is helpful to separate the two motions of the plane: (1) the motion produced by the propeller and (2) the motion produced by the wind.

We might think of the plane as first flying in calm air for one hour; then being blown by the wind for an hour, as if the plane were suspended from a balloon which drifted with the wind.

In Figure 190, AB is the projected air path of the plane. It is the path the plane would take if moved by the propeller only. BC is the path the plane would take if blown by the wind only. AC is the resultant of the two motions.

Construction lines

In representing the solution of wind-drift triangles in this book lines of different kind are used as follows:

Track or course — full line	————————
Projected air path — "dotted" line	- - - - - - - - - -
Trail — dash line	— — — — — —
Wind vector — heavy line	━━━━━━━━━━
Construction lines — light full lines	————————

It is not necessary to use precisely these symbols, but you will find it helpful to distinguish the different lines in some manner. It is helpful to place a "T" on the track to represent an airplane facing in the direction of the heading, as shown in Figure 190. This serves to identify both the track and the heading.

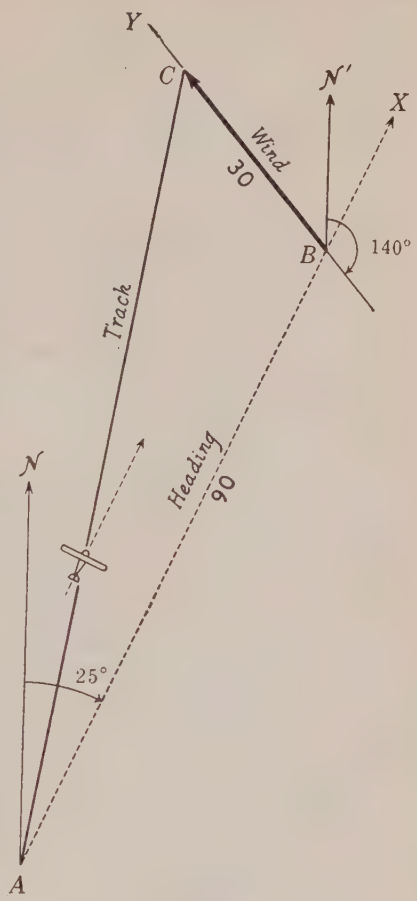


Fig. 190.

Exercise 1. What are the course and ground speed of a plane that is flying under the following conditions?

(*a*) air speed 80 miles per hour, heading 90°, wind from 195°, 10 miles an hour

(*b*) air speed 90 miles per hour, heading 190°, wind from 145°, 20 miles an hour

(*c*) air speed 100 miles per hour, heading 290°, wind from 200°, 30 miles an hour

Exercise 2. What is the wind-drift angle in each case in Exercise 1?

Note to Instructor. Exercises in this and the following chapters frequently contain three parts. You may feel that in some instances one or two are sufficient. Part (*c*) might be omitted, for example, and used later for review.

Making good a course

In the language of avigation, if the plane is moving over the ground in the direction of north, although headed to the right or left of north because of a side wind, it is customary to say that the plane is *making good a course* to the north.

Finding the heading and ground speed

Ordinarily in avigation a pilot does not have such a problem as finding which way he will fly if he *heads* north. The problem is more likely to be one of finding in what direction he must head the plane if he wants to *make good a course* to the north.

Looking at Figure 185, the problem might be: Knowing the direction AC of the course to be made good, the velocity of the wind (length and direction of AD), and the air speed (length of DC), what is the heading (direction of DC or AB) with which to make good the course AC?

PROBLEM 2. Given a required course whose direction is 15°, a wind velocity of 30 miles an hour from 140°, and an air speed of 90 miles an hour, what are the heading and the ground speed in making good the course?

METHOD. Draw the wind vector from the starting point. Then draw an air path (trail) to get back on the track in an hour.

SOLUTION. (See Fig. 191.)

1. From any point A draw a line AN to represent north.

2. Draw the desired course by a line AX, making an angle of 15° with AN.

3. From A draw wind vector AD (30 units long from 140°).

4. With D as center and a radius representing one hour's air path (90 units), draw an arc cutting AX. Call the point of intersection C.

5. Draw DC. The direction of DC is the heading necessary to make good the course AX. DC is the trail of the plane.

6. If we wish, we may draw AB parallel to DC to show the heading at A. Then we may measure angle NAB to find the heading. Of course, it is not necessary to draw line AB. The angle NOC is of the same size as the angle NAB. We can measure angle NOC to find the heading. In the figure the heading is about 31°.

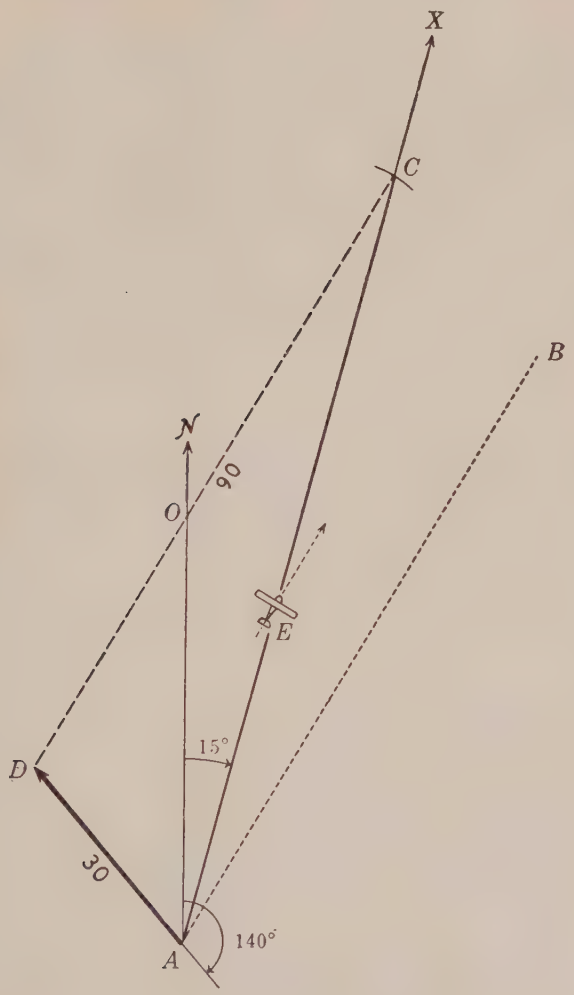


FIG. 191.

Remembering the solution

One way to remember the method of the solution is to think: I'll let the wind blow the plane for one hour first, then head the plane in such a way as to get back on the desired course in one hour.

Letting the wind blow the plane one hour first means, of course, drawing the wind vector from the starting point. Getting back on the course in one hour means finding a point on the course that is one hour's air-flying distance from the point to which the plane has theoretically been blown in one hour.

Another way to remember the solution is to think: I must find the trail of the plane for one hour's flight. The trail begins at a point to which a puff of smoke from A would blow in an hour.

Wind-correction angle

The angle at which you must head the plane to the right or left of a course in order to make good the course is called the *wind-correction angle.*

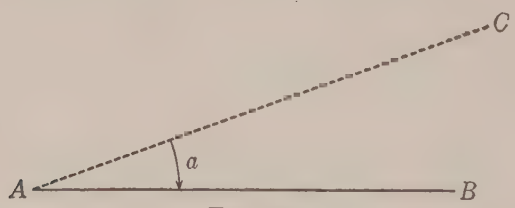


FIG. 192.

Thus, if AB in Figure 192 is the desired course and AC is the heading necessary to make good track AB —

(1) angle a is the *drift angle* with reference to the heading AC; but also

(2) angle a is the *wind-correction angle* with reference to the desired course AB.

EXERCISE 3. What is the heading and what is the ground speed of a plane flying under the following conditions?

	Air Speed (Miles per hour)	Course	Wind From	Wind Speed (Miles per hour)
(*a*)	100	135°	205°	30
(*b*)	120	260°	15°	25
(*c*)	130	330°	210°	35

EXERCISE 4. What is the wind correction angle in each case in Exercise 3?

EXERCISE 5. What is the heading and what is the wind correction angle for flying with an air speed of 100 miles an hour with an east wind at 20 miles an hour, (*a*) from Alfa to Berg on the Exercise Chart, page 297? (*b*) from Berg to Cape? (*c*) from Cape to Alfa?

Finding the compass heading when the wind is blowing

It is not proper to find the compass course necessary to make good a given true course and then to find the necessary heading to allow for wind drift. For one thing, the plane in that case is not heading in the direction for which the deviation was obtained. Moreover, you cannot solve a wind triangle in which the course is a compass direction and the wind a true direction (wind directions are always true directions).

You must first find the heading to allow for drifting from the true course. This will be the *true* heading. From the true heading you then find the magnetic heading, then the compass heading, in exactly the same manner as you found the compass course from the true course.

Finding the wind direction

We have seen how to find the *track* when we know the heading, the air speed of the plane, and the velocity of the

wind; also how to find the *heading* when we know the course, the air speed of the plane, and the velocity of the wind. There are occasions when it is desirable while flying to determine the wind velocity (speed and direction). This can be done in a variety of ways. Let us consider first finding the *direction* of the wind while flying, assuming the wind direction cannot be seen by means such as smoke.

If the plane is flying near enough the surface (say within a thousand feet), it is fairly easy to tell by looking at the ground below the plane whether or not the plane is drifting. If it is, we know the wind is blowing from the side.

One way, therefore, to determine wind direction at a low altitude is to turn the plane until the drift disappears.

If we are drifting to the right, we know that the wind is blowing from the left. Hence, if we turn to the right until the drifting disappears, we know that we are then flying directly down wind.

Finding the wind speed from the course, heading, and wind direction

Let us suppose we know the direction of the wind but do not know its speed. If we know the course and the necessary heading, we can find the wind speed, as shown in Problem 3.

PROBLEM 3. Let us suppose we are flying along a highway known to extend toward the northeast; we know the wind is from the east; the compass indicates that we are heading in the true direction of 55° (compass reading corrected for variation and deviation). Assuming an air speed of 100 miles an hour, what is the speed of the wind?

SOLUTION. 1. Draw a line AN to represent north (Fig. 193).

2. Draw a line AX to represent the course (45°).

3. Draw a line AY to represent the heading (55°).

4. On AY lay off AB to represent one hour's air path (100 units).

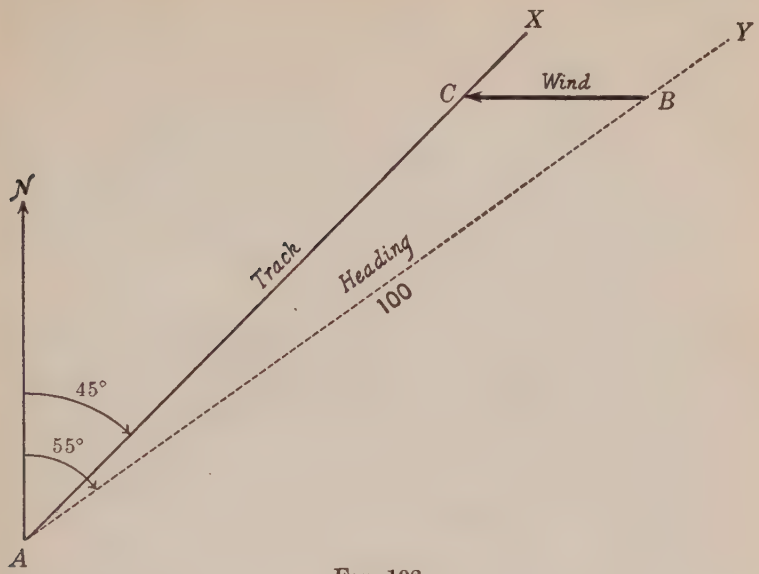


FIG. 193.

5. From B draw a line having the direction toward which the wind is blowing (west) cutting AX at C. This means cutting AX at some point and calling the point C.

6. BC is the wind vector. Its length tells the speed of the wind — one hour's motion. BC is about 24 units long; hence the wind is blowing at about 24 miles an hour.

EXERCISE 6. What is the speed of an east wind if a plane is flying under the following conditions?

	AIR SPEED	HEADING	TRACK
(*a*)	80 miles per hour	164°	173°
(*b*)	100 miles per hour	253°	257°
(*c*)	120 miles per hour	322°	314°

Finding the wind velocity from the heading, air speed, and a fix

Let us say that we have set out to fly in the direction AY (Fig. 194), heading the plane in the direction AY, disre-

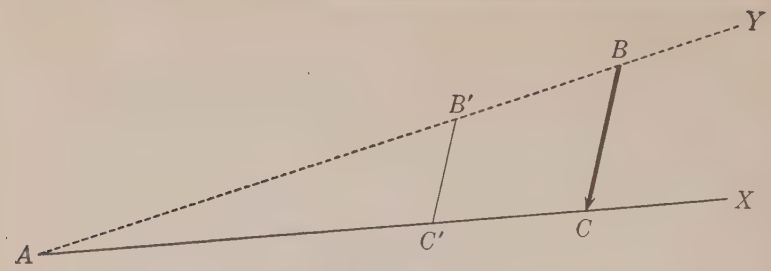


FIG. 194.

garding the wind. Let us say that after 40 minutes' flight we find ourselves at C', although we know from our air speed that we would be at B' if the air were calm; hence we know the wind is blowing.

We would call point C' a *fix* — meaning a location which was recognized or identified by the chart.

PROBLEM 4. What is the wind velocity (direction and speed) in the above case? Assume an air speed of 80 miles an hour.

SOLUTION. 1. Extend AB' to Y, to represent the projected air path, and lay off on AY a distance AB equal to one hour's air path (air speed).

2. Extend AC' to X and draw BC parallel to $B'C'$. BC is the required wind vector. Its length and direction show the wind velocity.

Remembering the solution

To find the wind vector from the heading, air speed, and a fix, remember: During the flying time the wind blew from the point where we would have been without wind to the point we reached. To find the wind motion for an hour, we extend the projected air path and track, first to find where we would be after one hour without wind and then to find where we would be after one hour *with* wind. Then we find the distance between these two points.

EXERCISE 7. What is the wind velocity if a plane with an air speed of 100 miles an hour leaving Fort —

(*a*) with a heading in the direction of Berg from Fort is at Eden in 60 minutes?

(*b*) with a heading in the direction of Eden from Fort is at Dale in 70 minutes?

(*c*) with a heading in the direction of Cape from Fort is at Dale in 80 minutes?

Need for a measure of drift

In Problem 3 we assumed that we knew the direction of our track, because we were flying along a highway of known direction. It is often desirable to find out the direction of the track when we are not following any landmark of known direction. A *drift indicator* is helpful in such a case.

Drift indicator

A drift indicator is a device for measuring the drift angle of a plane flying in a wind.

The principle on which the conventional drift indicator is based is as shown in Figure 195. The instrument is placed where the pilot can look downward through it (from an eyepiece, perhaps) and see the motion of the ground. A hair line in the instrument is rotated until it is parallel with the motion of the ground as it appears to pass under the plane. The hair line is then in the direction in which the plane is moving over the ground. The angle the hair line makes with the longitudinal axis of the plane is then read from a scale. It is the *drift angle.*

The direction of the hair line is the direction of the track; the direction of the axis of the plane is, of course, the heading. The drift angle is to the *right* if the hair line is to the *right* of the axis — that is, if the track is to the right of the heading.

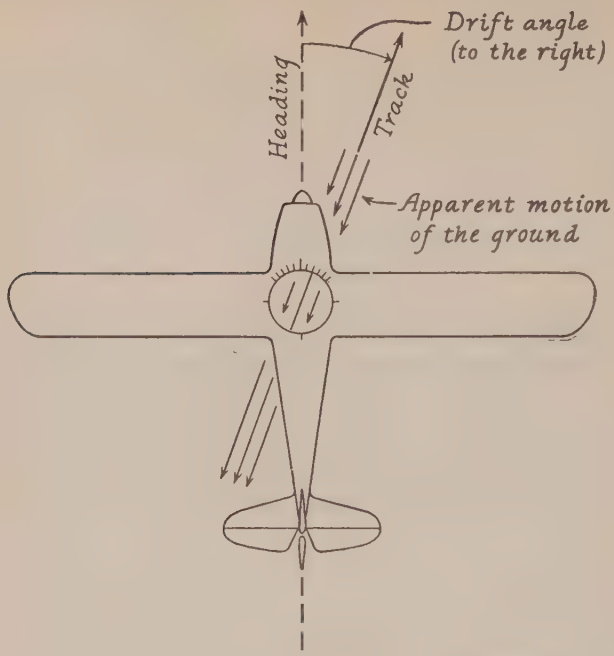


FIG. 195. The principle of the drift indicator.

Finding the wind velocity from two drift angles

If we have a drift indicator, we can find the wind velocity from two observations of drift.

To understand the method of solution, let us suppose two planes fly in different directions AV and AV' from a point A for an hour, each at a 100-mile air speed and each leaving a smoke trail, as shown in Figure 196. If the wind blows from A to C in one hour, we know that after one hour each smoke trail will begin at C and the two smoke trails will be of equal length; hence the planes will be B and B', assuming CB and CB' to be equal.

The method of solution is to draw a figure similar to Figure 196, beginning at C, drawing the trails first, then drawing the courses backward, thus finding point A.

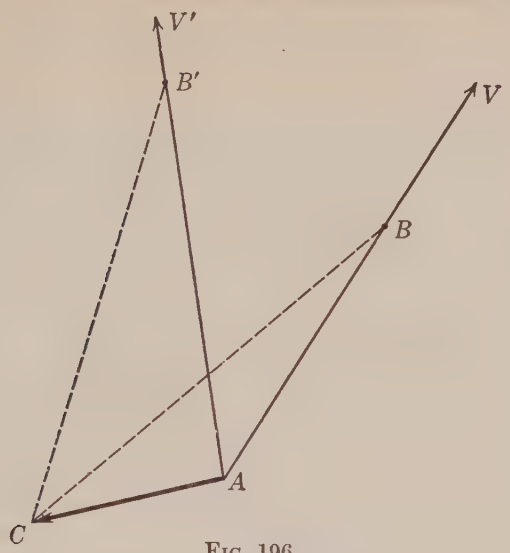


FIG. 196.

PROBLEM 5. Suppose we are in flight and wish to redetermine the wind velocity. We are flying with a heading of 30° and note a drift angle of 10° to the right. We fly a few moments with a heading of 300° and note a drift angle of 15° to the left. (Air speed 90 miles an hour.)

What is the wind speed and direction?

SOLUTION. 1. Choose a point C to represent point C of Figure 196.

2. Draw CX in the direction of the first heading (30°) to represent the direction of one trail. (See Fig. 197.)

3. Draw CX' in the direction of the other heading (300°), to represent the direction of the second trail.

4. Lay off CB on CX and CB' on CX' equal to one hour's air path (to show the lengths of the trails).

5. Lay off an angle XBY equal to the first drift angle (10° to the right).

6. Extend course BY backward to some point Z.

7. Lay off an angle $X'B'Y'$ equal to the second drift angle (15° to the left).

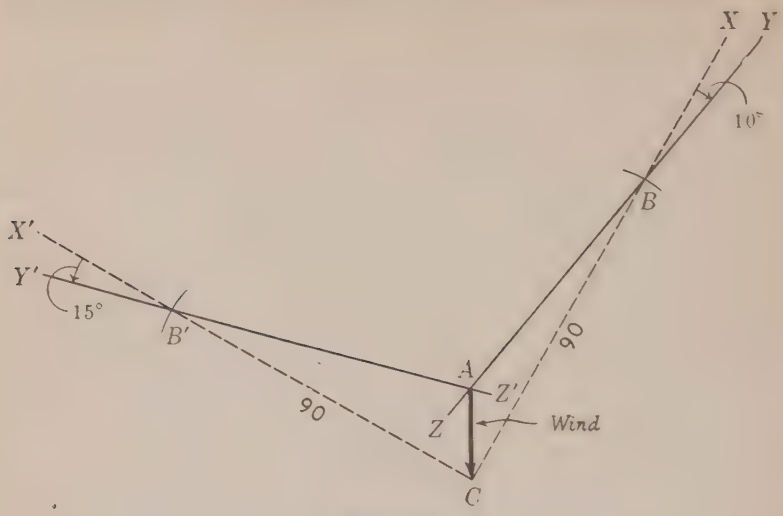


FIG. 197.

8. Extend course $B'Y'$ backward, cutting YZ. Call the point of intersection A.

9. Draw AC. AC is the wind vector. $AC = 24$ units, from 0°. The wind blew from the north at about 24 miles an hour.

Remembering the solution

To remember this solution, think: I must draw the two trails beginning at the same point, lay off the drift angles, and "back track," to find the starting point of the two tracks.

EXERCISE 8. What is the wind velocity if a plane with an air speed of 90 miles an hour flies —

(*a*) first with a heading of 45° and drift angle of 20° to the left and then with a heading of 125° and drift angle of 20° to the right?

(*b*) first with a heading of 10° and drift angle of 20° to the left and then with a heading of 30° and drift angle of 18° to the left?

(*c*) first with a heading of 20° and drift angle of 22° to

the right and then with a heading of 350° and drift angle of 25° to the right?

EXERCISE 9. Sketch a wind triangle to show the heading directly east and the wind blowing from the north. The wind vector divided by the air-speed vector is what trigonometric function of the drift angle?

EXERCISE 10. What is the drift angle in Exercise 9 if the air speed is 80 miles an hour and the wind speed is 39 miles an hour?

EXERCISE 11. What is the wind speed in Exercise 9 if the air speed is 80 miles an hour and the drift angle is 20°?

EXERCISE 12. Sketch a wind triangle to show a desired course directly east and a wind from the north. The wind vector divided by the air-speed vector is what trigonometric function of the wind-correction angle?

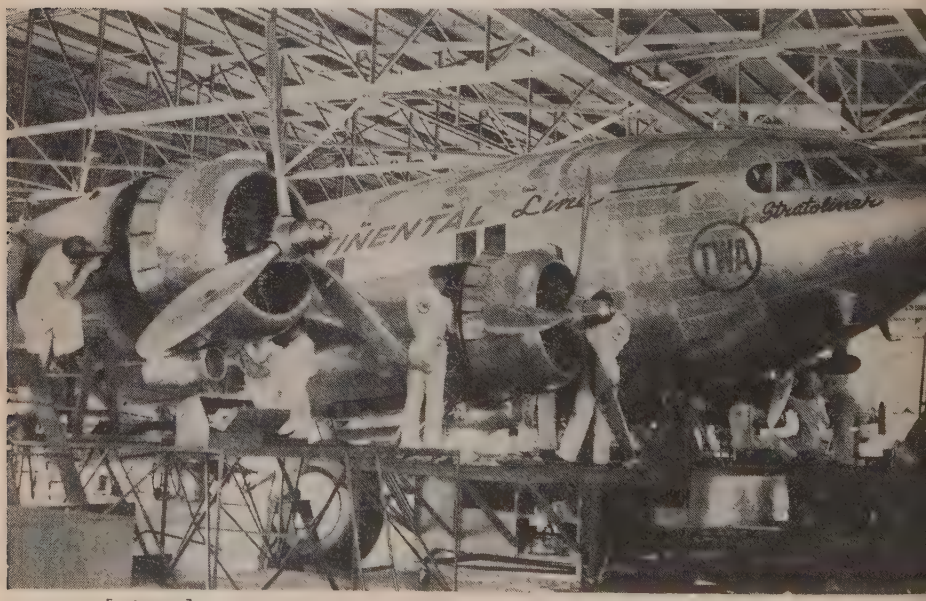
EXERCISE 13. What is the wind-correction angle in Exercise 12 if the air speed is 80 miles an hour and the wind speed is 40 miles an hour?

QUESTIONS

1. What is a heading?
2. What is a track?
3. What is a wind vector?
4. What is a drift angle?
5. What is crabbing?
6. What is meant by air speed?
7. What is meant by ground speed?
8. What is meant by a wind-drift triangle?
9. What is meant by drawing to scale?
10. What is a protractor?
11. How would you improve the convenience of an inch scale for letting $\frac{1}{16}$ inch represent a mile?
12. What is meant by wind velocity?
13. How would you find the course or track of a plane and the ground speed if you had the heading, the air speed, and the wind velocity?

14. Toward what direction is an east wind blowing? a wind from 170°? a wind from 270°?
15. What does it mean to "make good a course"?
16. How would you find the heading necessary to make good a given course?
17. What is the difference between a wind-correction angle and a wind-drift angle?
18. What ways can you describe for finding the wind vector?
19. Can the wind velocity be found from a heading, air speed, and drift angle?
20. Can the wind velocity be found from the heading, drift angle, air speed, and wind direction?

FIG. 198. A Stratoliner of the Transcontinental and Western Air Lines (Boeing 307 B) undergoing routine maintenance. The Hamilton hydromatic propellers have variable pitch, constant speed, and full feathering. The bulbous nose on each hub is a piston-and-cylinder-oil hydraulic mechanism which varies the pitch and does the feathering. The "gills" behind the engine cowling, called *cowl flaps*, are used for regulating the temperature of the cylinders. Airplanes must always be in perfect mechanical condition. There are several mechanics on the ground for each pilot in the air.



24

INTERCEPTION

THERE is a group of problems relating to the overtaking of a moving body such as a ship, train, or another airplane which it is valuable to understand and which may involve principles other than those you have studied. These are called *interception problems.*

This chapter deals with interception problems. It begins with some simple problems, then treats more difficult ones.

Nautical miles

On land it is customary to measure distance in statute miles. One *statute mile* equals 5280 feet. On the ocean it is customary to measure distance in nautical miles. One *nautical mile* equals 6080.2 feet. A nautical mile is therefore about $\frac{38}{33}$ of a statute mile, or it is about 1.15 times as long as a statute mile.

In this chapter "miles" will be understood to refer to nautical miles unless otherwise specified.

Knots

A *knot* is a unit of speed. One knot is one nautical mile per hour. Sailing at 20 knots means sailing at a speed of 20 nautical miles per hour.

The term "knot" is sometimes used loosely to mean nautical miles. You sometimes hear the expression, "twenty knots an hour." The words "an hour" are unnecessary when so used. What is meant is 20 nautical miles per hour, or 20 knots.

Intercepting a ship at a given time

Let us say that an ocean liner leaves port A (Fig. 199) at 8 : 00 A.M. and sails eastward at 25 knots. Let us say that a plane is to leave an airport at B to fly out, meet the vessel at a given distance from shore, drop a bag of mail, and return to the airport.

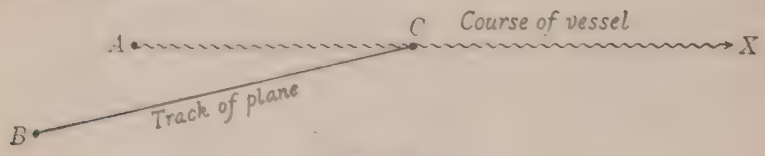


FIG. 199.

PROBLEM 1. Assuming that there is no wind and that the plane will fly at an air speed of 100 miles an hour, in what direction must the plane fly and when must it leave B in order to meet the ship at a point C, 200 miles from shore?

Obviously, since there is no wind the plane can head directly toward C; hence its track and heading are the same and both are represented by the line BC.

You may well be able to tell how to solve this problem without the help that follows. Try to do so.

SOLUTION. 1. Draw a line AX to represent the eastward course of the ship. (See Fig. 199.)

2. Find a point C on AX, such that AC represents 200 miles.

3. Draw BC. BC represents the track and heading. Find the direction of BC to obtain the heading.

4. To find the time required for the trip out, measure BC to find the air distance to be flown and divide this by the air speed of the plane (100 miles).

5. Find the time the ship will be 200 miles from A by (*a*) dividing 200 miles by 25 miles (one hour's sailing) to find the time the vessel will have been sailing and (*b*) adding this to 8 : 00 A.M.

6. Find the hour at which the plane must leave, by subtracting the flying time from the hour the vessel will arive at C.

Exercise 1. Airport B is 60 miles south of seaport A. A vessel leaves seaport A at midnight and steams eastward at 25 miles an hour. Assuming no wind, when must a plane leave B, flying with an air speed of 120 miles an hour, and in what direction must it fly, in order to intercept the vessel (*a*) at 300 miles from A? (*b*) at 350 miles from A? (*c*) at 400 miles from A?

Intercepting a vessel in a given flying time

A plane sometimes flies out to a vessel at sea, lands on the water, is picked up by a crane, and continues on with the vessel. The plane may then be catapulted from the vessel when within flying distance of the destination and land ahead of the vessel to hasten the delivery of mail.

Let us say that 5 hours is considered the maximum safe flying time for the trip out to the vessel, and that it is desired to set a starting time as late as possible in order to pick up late mail. We may then have a problem of the following type.

Problem 2. Assume the following conditions:

(1) No wind;

(2) the vessel sails east from seaport A at 8 : 00 A.M. at 25 miles an hour;

(3) the plane leaves airport B at a later time with an air speed of 150 miles an hour, to overtake the vessel in just 5 hours. (A and B are presumed to be points on an aeronautical chart, situated relative to one another as shown in Figure 200.)

How late may the plane leave the airport?

This problem also is fairly easy. Try to tell how to solve it before reading the solution.

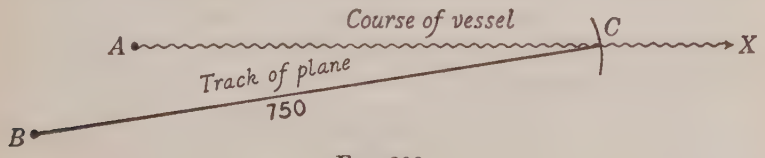


Fig. 200.

SOLUTION. 1. Draw a line AX, representing a direction east from A (Fig. 200).

2. Find the distance the plane can fly in 5 hours (5×150 miles = 750 miles).

3. With B (the airport) as a center and a radius representing 5 hours' flight (750 units), draw an arc cutting AX at C.

4. Draw BC. BC is the track and heading.

5. Measure AC. Divide its length by 25 to find the number of hours the vessel has been sailing. (In Figure 200, AC = 610 units representing $24\frac{2}{5}$ hours.) Find the hour the vessel will arrive at C. (8 : 00 A.M. + $24\frac{2}{5}$ hours = 8 : 24 A.M., next day.)

6. Find the time the plane may leave. (The plane may leave the next day at 8 : 24 A.M., − 5 hours or 3 : 24 A.M.)

EXERCISE 2. Airport B is 90 miles southeast of seaport A. On a calm day a vessel steams east from A at midnight at 30 miles an hour. A plane has an air speed of 120 miles an hour. At what time may the plane leave and in what direction must it fly in order to overtake the vessel (*a*) in just 3 hours? (*b*) in 4 hours? (*c*) in 5 hours?

Intercepting a vessel in a given flying time, with the wind blowing

Problem 2 was fairly simple: but it was based on a situation rather unlikely to occur, because there was no allowance for wind. Let us now solve such a problem, assuming the wind to be blowing.

PROBLEM 3. Let the conditions be as follows:

(1) The wind is blowing from 350° at 20 miles an hour;

(2) the vessel sails east from seaport A (Fig. 201) at 8 : 00 A.M., at 25 miles an hour;

(3) the plane starts later from airport B with an air speed of 100 miles an hour, to overtake the vessel in 5 hours.

How late may the plane leave?

SOLUTION. 1. Draw AX to represent the eastward course of the ship.

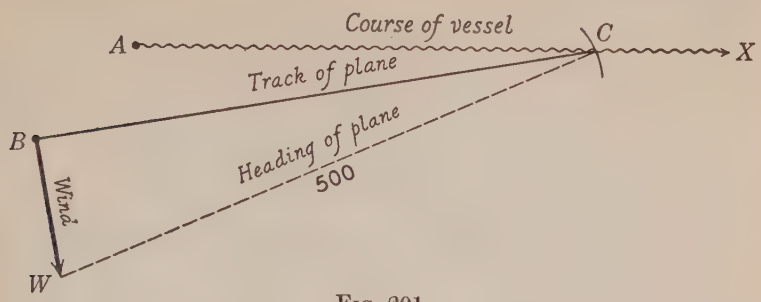


FIG. 201.

2. Draw a wind vector BW, as shown in Figure 201 (to represent the full 5 hours' motion of the air).

3. With W as center and a radius representing 5 hours' air flight (500 units), draw an arc cutting AX at C. C is the point on the course of the vessel which the plane can reach in a straight line from B in just 5 hours. The plane may leave at a time such that it will arrive at C just when the ship does.

4. Draw WC. WC is the heading, BC is the track, and AC is the distance the vessel will be from shore when met by the plane. WC is the trail of the plane, as of the time of arrival at C.

5. Find the time the vessel will arrive at C, and subtract 5 hours to find the time the plane may leave B.

Remembering the solution

To remember the solution, just think: I will let the wind do all its blowing first (imagining the plane to be drifting for 5 hours attached to a balloon). Then I must find a point on the vessel's course 500 miles from the point to which the plane might have drifted in 5 hours before it started to fly.

EXERCISE 3. Airport B is 50 miles N. E. of seaport A. A vessel steams east from seaport A at midnight at 22 miles an hour. When may a plane with an air speed of 80 miles an hour leave airport B to overtake the vessel in 3 hours if the wind is (*a*) from 180° at 20 miles an hour? (*b*) from 120° at 15 miles an hour? (*c*) from 20° at 30 miles an hour?

EXERCISE 4. If the average magnetic variation is 18° E. on the trip and the deviation is as in the deviation chart on page 307, what will the compass heading need to be in each case in Exercise 3?

Constant bearing means collision

There is an old maritime saying that "Constant bearing means collision."

You can see easily why this is so. For example, let us suppose two ships are sailing, one on the course SS' and the other on the course TT' (Fig. 202). If ship S is at A when ship T is at A', and ship S is at B when ship T is at B', and so on, and AA', BB', and so on, are in the same direction, we would then say that the bearing of either ship from the other is constant. You can easily see that if the ships continued these courses they would collide at some point P.

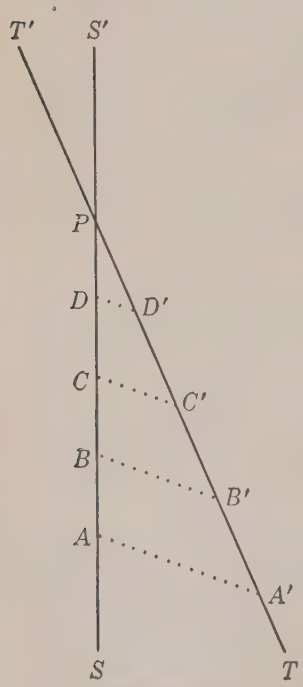


FIG. 202.

On the other hand, if the bearing (direction) of one vessel from the other is changing as shown in Figure 203, we know that one vessel will cross in front of the other.

If the *bearing* of ship S from ship T is moving in the direction that ship S is moving, as shown in Figure 203, ship S will cross ahead of ship T. But if the bearing of ship S from ship T is moving in the direction opposite from that of the motion of ship S, then ship S will pass behind ship T.

We all understand these consequences of a moving bearing as we drive or ride in a car and see another

car approaching from the side. And in flying we must keep them well in mind.

For example, we might be flying northward at 80 miles an hour and see a plane approaching from the east at the same altitude in a direction of about 70° and think we had plenty of opportunity to pass in front of it.

But let us say that as we fly from A to B, as shown in Figure 204, we happen to observe that the other plane is still in the same direction from us (that the bearing is constant). We know then that the other plane is approaching very rapidly (about 220 miles an hour in this case) and will collide with us at some point P "if we don't watch out."

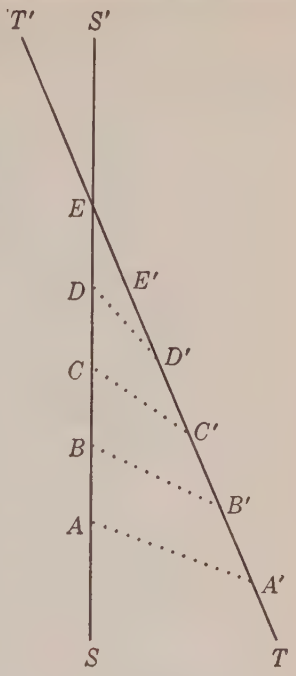


Fig. 203.

Would you know how to obtain the speed of the second airplane in Figure 204?

Suppose that vector AP in Figure 204 represents the speed of the first plane. $A'P \div AP$ = what trigonometric

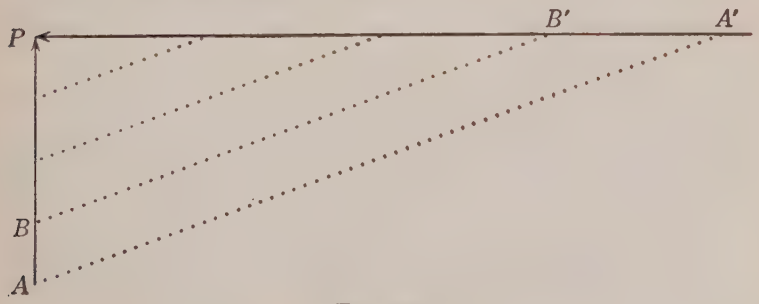


Fig. 204.

function of angle PAA'? Tan 70° = ? 2.747 × 80 m.p.h. = ? m.p.h. (speed of second plane).

In Figure 204, AP and $A'P$ may represent either the ground speeds of the two planes or the air speeds. The principle applies in either case.

EXERCISE 5. Vessel A is sailing in the direction 45°. Vessel B is sailing in the direction 315°. The bearing of vessel A from vessel B is moving to the right. Which vessel will pass in front of the other?

EXERCISE 6. Plane A is flying northward with a ground speed of 90 miles an hour. From the direction of 300° plane B is approaching with a constant bearing. What is the ground speed of plane B (*a*) if it is flying eastward? (*b*) if it is flying northeast?

Intercepting a vessel as soon as possible

Problems 2 and 3 had to do with overtaking a vessel as *late* as possible. A different kind of problem is one in which the pilot wishes to overtake a vessel as *soon* as possible. This might be the situation, if the plane were taking mail that closed at a certain time, established beforehand.

PROBLEM 4. (1) Assume that there is no wind.

(2) The vessel sails east from port A at 8 : 00 A.M., at 25 miles an hour.

(3) The plane starts from airport B (Fig. 205) with an air speed of 100 miles an hour, to overtake the vessel as soon as possible.

(4) For convenience let us assume that the plane leaves B at the same time the vessel leaves A.

What is the heading, and how long will it take the plane to overtake the vessel?

In solving a problem in overtaking a vessel we find it helpful to make use of the principle that "constant bearing means collision" (or meeting).

SOLUTION. 1. Draw a line AX to represent the eastward path of the vessel. (See Fig. 205.)

2. Lay off vector AC to represent one hour's motion of the vessel (25 units).

3. Draw CY parallel to AB. The plane must be on CY at the end of the hour in order to keep the vessel at a constant bearing.

4. With B as a center and a radius representing one hour's air path of the plane (100 units), draw an arc cutting CY at D. The plane should be at D in one hour.

5. Extend BD to cut AX at E. The plane will meet the ship at E.

6. Measure BE, and divide the distance flown by the air speed to find the time required.

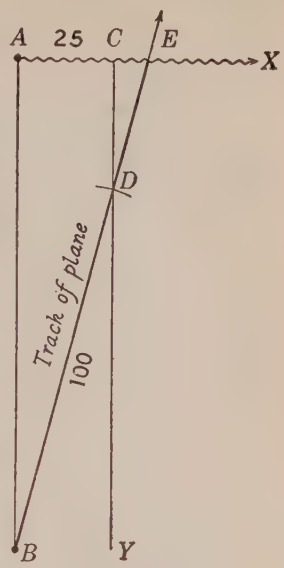


FIG. 205.

Remembering the solution

To remember the solution, just think: I must keep the bearing constant (bearing of vessel from plane). In one hour I must be on a line from the vessel parallel with the direction of the vessel from the plane at the start. I must also be one hour's flight distance (air speed) from the starting point.

Alternate solution

There is an alternate method of solving Problem 4. We may draw the vessel's vector AC in the opposite direction from B, as shown by BB' in Figure 206. Then we may find D' on AB, instead of D on CY. $B'D'$ is the heading, the same as BD. We have then to draw the track BE from B, parallel to $B'D'$. Triangle $D'BB'$ in Figure 206 corresponds to triangle DYB in Figure 205. One solution is as easy as the other.

Plane leaving later than the vessel

If the plane is leaving after the vessel has been under way for some time the solution is the same, except that we use point A', the position of the vessel at the time the plane leaves point B, as shown in Figure 207. In this case the vessel is not always north of the plane, as in Figure 205, but is always in the direction BA' from the plane.

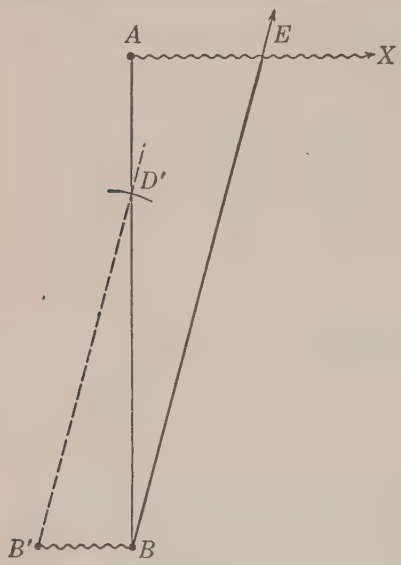


Fig. 206.

The alternate method given above may be used also in solving this problem. That is, we may lay off the vessel's vector backward from B and swing an arc cutting BA at D', as before.

Exercise 7. Airport B is 400 miles east of airport A. On a calm day a bombing plane leaves airport B at 6 : 00 A.M., flying a course in the direction 290° at 180 miles an hour. A pursuit plane with an air speed of 270 miles an hour takes off at A at 6 : 15 A.M. to intercept the bomber as soon as possible. How soon can it do so and what must be its true heading?

Exercise 8. How soon could a pursuit plane as in Exercise 7 intercept the bomber, if the pursuit plane could fly at 300 miles an hour and left at 6 : 20 A.M., and what would be its heading?

Intercepting a vessel, as soon as possible, with wind

Let us now consider the problem of overtaking a vessel as soon as possible, when the wind is blowing. It makes no

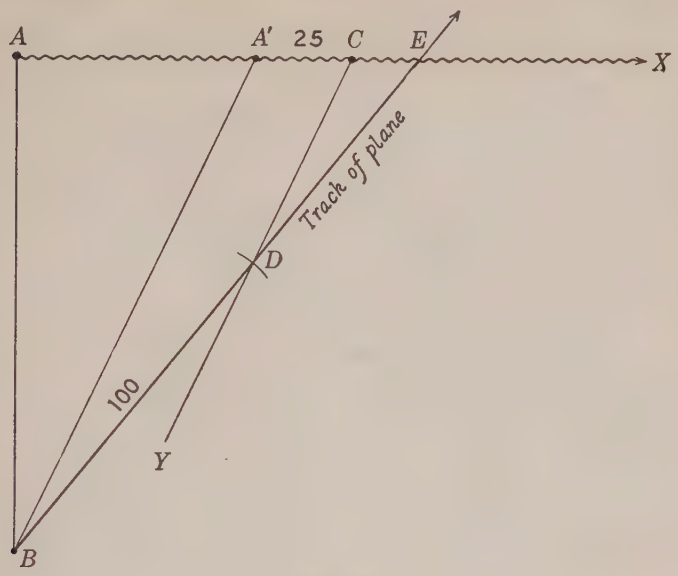


FIG. 207.

difference in the method of solution whether the vessel is starting from shore or from a point some distance from shore when the plane starts to overtake it; so let us assume that the vessel is already at a known position A' some distance from shore when the plane starts.

PROBLEM 5. Let us assume the conditions to be as follows:

(1) The vessel leaves port A at a given time and sails eastward at 25 miles an hour;

(2) the plane leaves airport B (see Fig. 208) later and flies with an air speed of 100 miles an hour to overtake the vessel as soon as possible;

(3) the vessel is known to be at A' when the plane leaves airport B;

(4) the wind is blowing from 135° at 20 miles an hour.

How long will it take the plane to overtake the vessel, and what is the heading and what is the track?

SOLUTION. In planning the solution let us take advantage of our knowledge that "constant bearing means collision." The steps are as follows:

1. Draw $AA'X$ to represent the eastward path of the vessel. (See Fig. 208.) Draw $A'B$.

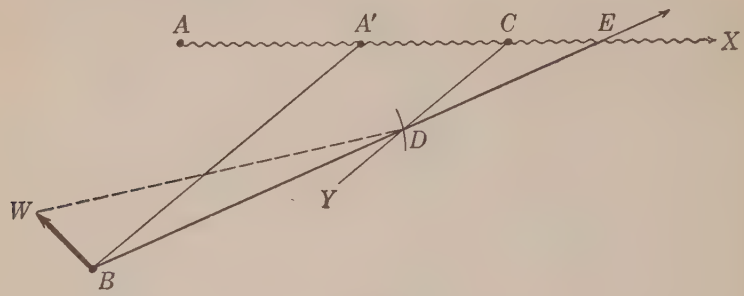


FIG. 208.

2. Find point C such that $A'C$ is the vessel's vector (one hour's sailing).

3. Draw a line CY from C parallel to $A'B$. (If the pilot is on this line in just one hour, he is keeping the ship at a constant bearing.)

4. Draw BW, the wind vector.

5. With W as center and a radius equal to one hour's air path of the plane (100 units), draw an arc cutting CY at D. (WD represents one hour's air path; hence the direction of WD is the heading of the plane, and BD is the track of the plane for one hour. Thus we see that the pilot is maintaining the vessel at a constant bearing.)

6. Extend BD to cut AX at E. E is the point where the plane will overtake the vessel. BE is the track of the plane. AE is the distance the vessel will have sailed.

7. Measure $A'E$ and divide its length by the speed of the vessel to find the time required to overtake the vessel after it left A'. Or measure BE and divide it by the air speed.

Remembering the solution

Just think: I must find a line on which the pilot must be after one hour, so that the bearing of the vessel from the plane will be the same as at the time of starting. Then I

can find the heading by supposing that the plane drifts for one hour without flying and then flies in still air a direction necessary to get to the required line in one hour.

It is customary in an actual case of this kind to use a vector for the vessel's motion slightly longer than the true vector, in order that the plane will arrive on the course slightly in advance of the vessel. The plane then turns back on the vessel's course and meets it from in front.

EXERCISE 9. Airport B is 90 miles northeast of airport A. A bombing plane leaves airport A and flies with a ground speed of 180 miles an hour on a course in the direction 280°. The wind is blowing from 170° at 40 miles an hour. A pursuit plane of air speed 300 miles an hour leaves airport B 10 minutes later to intercept the bombing plane as soon as possible. How soon may the pursuit plane intercept the bomber, and what heading must it use?

Flying to shore from a vessel

Considering that, when flying to shore from a vessel, the destination is stationary, the problem of finding when to start the flight is very simple. It merely involves finding the point on the course of the ship *to* which a plane can fly from the airport in its safe flying time, as in Problems 2 and 3. That is also the point on the vessel's course from which this plane can safely fly to the airport.

Flying out to meet a vessel

There is no important difference between flying to overtake an outgoing vessel and flying to meet an incoming one. In either case you meet the vessel at a point on its course. About the only difference is that the vessel is presumably getting farther away from the airport in the first case and nearer in the second. Hence you must be careful not to start too late to overtake a vessel nor too early to meet one.

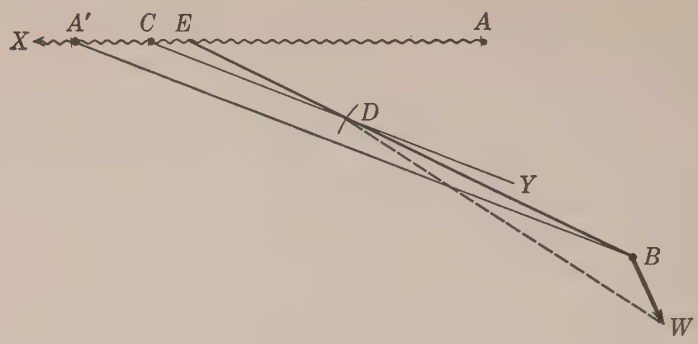


FIG. 209.

PROBLEM 6. A vessel is due to arrive at port A from the west at 7 : 30 P.M. (Fig. 209). A pilot wishes to leave airport B at 2 : 00 P.M. to meet the vessel. His air speed is 100 miles an hour. (Wind velocity is shown by vector BW.) What is his heading? When will he meet the vessel?

SOLUTION. 1. Draw a line XA to represent the vessel's course, and find point A' at which the vessel will be at 2 : 00 P.M.

2. On $A'A$ lay off $A'C$ to represent one hour's sailing of the vessel.

3. Draw CY parallel to $A'B$.

4. Draw BW, the wind vector.

5. With W as center and a radius equal to one hour's air path, draw an arc cutting CY at D. WD is the heading.

6. Draw BD, the course, and extend it to cut $A'A$ at E. DC is the same bearing as BA'; hence the plane will meet the ship at E.

7. BD = ground speed = 84 miles an hour.

8. BE = 130 miles, to be flown.

9. Flying time $= \frac{130}{84} \times 60 = 93$ min.

10. 2 : 00 P.M. + 93 min. = 3 : 33 P.M. (time of meeting).

Remembering the solution

Think: I must find a line parallel to the bearing of the ship from the plane at the start, on which line I must be at

the end of one hour, to keep the bearing of the ship the same. I can suppose that the plane drifts for an hour, then find the direction to fly in order to be on the required parallel at the end of one hour. This solution is the same as the solution for Problem 5.

EXERCISE 10. A vessel steaming at 24 miles an hour is due to arrive at port A from the east at 7 : 00 P.M. The wind is from 4° at 25 miles an hour. A pilot whose plane has an air speed of 120 miles an hour leaves airport B, 40 miles south of A, at 1 : 00 P.M. to meet the ship. What is his heading, and when will he meet the vessel?

Plane flying the course of the vessel

Let us assume that a vessel sails from port A on a course to the east, and that a plane leaves later from the same point A to overtake the vessel. Assume there is no wind.

In that case the course of the plane is the same as that of the vessel, and the heading is also the same; hence it is not possible to use the method of Problem 5, because the course of the plane does not intersect the course of the vessel, as in Problem 5, to give us a point (E) at which the plane will overtake the vessel.

The bottom line AX in Figure 210 shows a plane starting to overtake a vessel. The next line above shows the same plane and vessel one hour later. The third line shows the same plane and vessel two hours later; and so on. We see that if the lines are equally spaced the positions of the ship lie in a straight line, and the positions of the plane lie in a straight line.

Representing time on the graph

When the plane's course and heading are the same as the vessel's course it is convenient to solve the problem *graphically* (by lines) by representing time on the graph, as in Figure 210. This is done as illustrated in Problem 7.

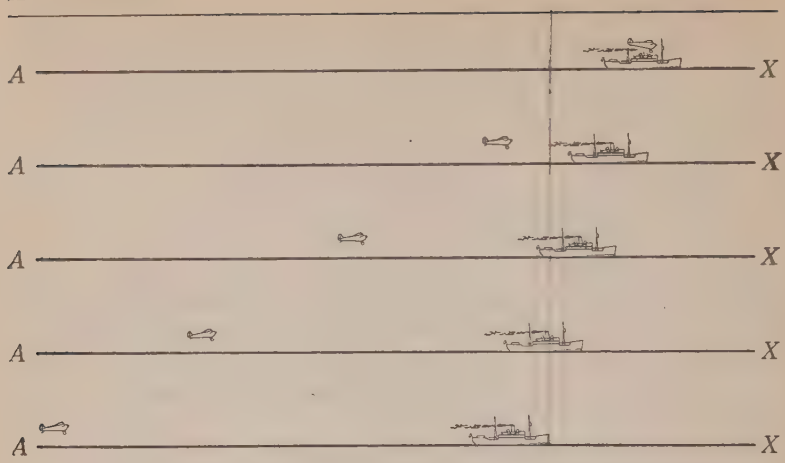


FIG. 210.

PROBLEM 7. A vessel has left port A and is steaming on a course east-northeast at 30 miles an hour. A plane leaves port A at a time when the vessel is known to be 300 miles from A, to overtake the vessel. The plane has an air speed of 150 miles an hour, and there is no wind.

How far from port A and in how many hours will the plane overtake the vessel?

METHOD. In a problem of this kind the plane and vessel are traveling in the same direction and the heading of the plane is the same as the direction of travel. We know this direction, and hence in the solution of the problem we are concerned with time and distance only. In the solution, therefore, we do not need to draw a course in any particular direction. This fact makes it possible to solve the problem conveniently on cross-ruled paper, as shown in Figure 211.

SOLUTION. 1. On a piece of cross-ruled paper as shown in Figure 211, draw horizontally a line AX to represent the course of the ship and plane.

2. Mark a convenient scale of miles along AX as shown.

3. Draw a vertical line AY as shown, to represent time.

4. Mark a convenient time scale along AY. (Let A represent the starting time and mark "1 hour" 12 units from A, so that each

unit represents 5 minutes. If desired, draw heavier lines to represent the even hours.)

5. Place a point B on AX to represent the distance of the vessel from A (300 miles) when the plane starts.

6. Consider the 1-hour line ($A'X'$) as representing AX one hour later. Place a point C on the 1-hour line to show the distance of the plane from A in one hour. That is, let $A'C$ represent 150 miles according to the miles scale along AX.

7. Also on the 1-hour line place a point D to show the distance of the ship from A in one hour. (Let $A'D = 300 + 30 = 330$ miles.)

8. As a check, place points E and F on the 2-hour line to show the position of the plane and vessel on AX after two hours. (E at 300 and F at 360.)

9. Draw BZ through D and F. This line indicates the progress of the vessel along AX.

10. Draw AZ' through C and E. This line represents the progress of the plane along AX.

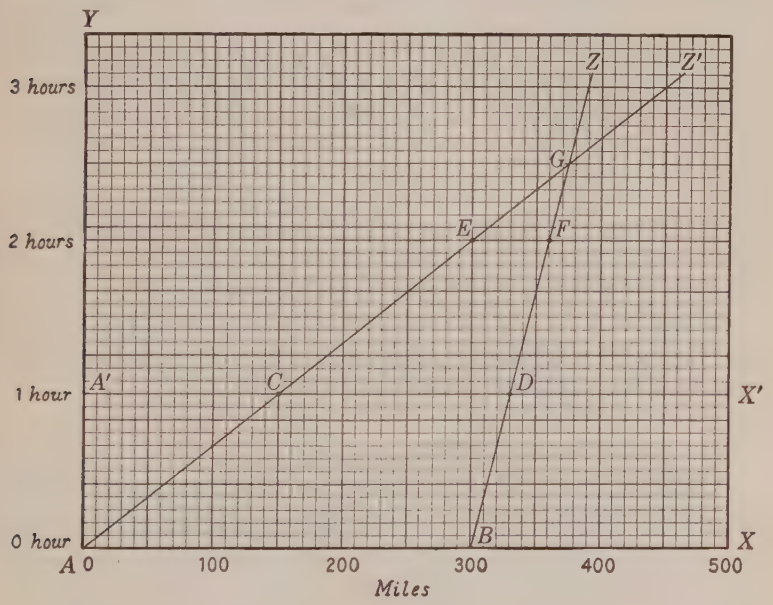


Fig. 211.

11. Call the point of intersection G, as shown. Point G indicates the time and distance from A at which the plane overtakes the vessel.

12. Read the distance on the scale of miles. G is on the vertical line representing a distance of 375 miles. The plane overtakes the vessel 375 miles from A.

13. Read the time along the time scale. G is on the horizontal line representing $2\frac{1}{2}$ hours. The plane overtakes the vessel in $2\frac{1}{2}$ hours.

Remembering the solution

We may think of Figure 211 as a series of pictures of AX taken an hour apart. The horizontal line on which G lies is the picture of AX taken just $2\frac{1}{2}$ hours after the plane started.

Remember that in this solution no angles are considered. We have only successive pictures of the one line on which the plane and vessel are traveling. The vertical dimension of the graph measures time only. The horizontal scale measures distance in whatever the direction of the motion.

Obviously, this method is as applicable to a problem of a plane's overtaking a plane as it is to a problem of a plane's overtaking a vessel.

EXERCISE 11. A vessel starts from seaport A at noon and travels due south at 24 miles an hour. A plane with an air speed of 100 miles an hour leaves the airport at A 3 hours later to overtake the vessel and deposit late mail. When will the plane overtake the vessel, and how far will the vessel be from seaport A when overtaken?

Flying with wind blowing

If the wind is blowing, the speed of the plane in the direction in which it is moving, which we are assuming is the same as the course of the vessel, is not the air speed of the plane but its ground speed. Hence the ground speed must be determined in the usual manner and used in the

graph for determining the time and position at which the plane overtakes the vessel.

EXERCISE 12. When and where will the plane in Exercise 11 overtake the vessel if the wind is blowing (*a*) from the north at 30 miles an hour? (*b*) from the southeast at 40 miles an hour?

Measuring time by distance

A pilot often needs to know the air distance he can fly in a given time. For this purpose he should make up a scale to convert distance on the chart into terms of time.

PROBLEM 9. A pilot's cruising speed is 95 miles an hour. Construct a scale by which to measure distance on the chart in terms of hours and minutes.

SOLUTION. 1. Select a sheet of paper accurately ruled, as shown in Figure 212; choose a point A on one of the lines, and from A label the lines 0, 10, 20, 30, and so on, as shown.

2. With A as center and a radius equal to 95 miles (air speed) on the scale of miles of the chart, draw an arc cutting the 60 line at C.

3. Draw AC.

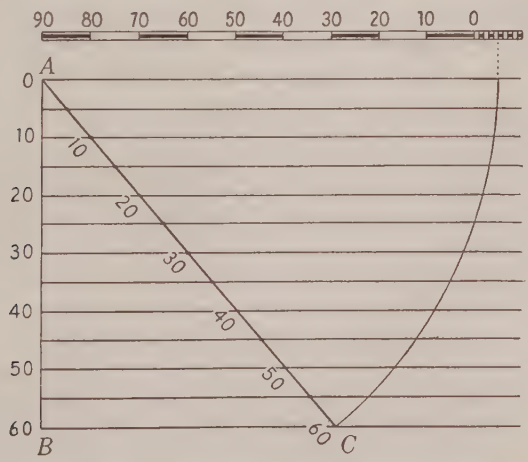


FIG. 212. The construction of a time scale.

4. Mark where the lines of the paper cut AC, as shown. Label the points 10, 20, 30, and so on, as shown. AC is the required scale. Fold or cut the paper on AC, in order to measure distance on the map in terms of minutes.

EXERCISE 13. Construct scales for finding the time required to travel various distances at a ground speed of 70, 80, 90, and 100 miles an hour, when the scale of miles on the chart is 20 miles to the inch.

Finding one's location at a given time

It is often necessary while flying to determine where one is, or was, or will be, at a given time.

PROBLEM 10. Let us say a pilot is flying on an eastward course AX with a heading of 70°, as shown in Figure 213;

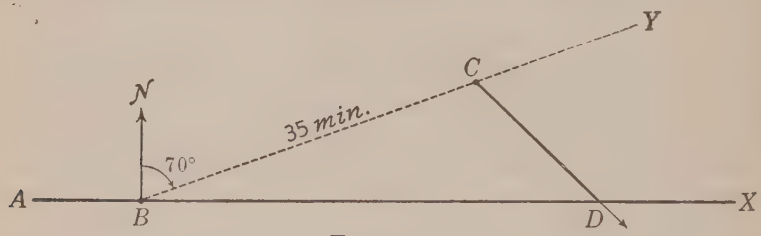


FIG. 213.

his air speed is 120 miles an hour; the wind is blowing from the northwest; he is now at B. Where will he be in 35 minutes?

One method is to find the ground speed by solving a one-hour wind-drift triangle and multiplying the ground speed by the time ($\frac{35}{60}$ hour). There is an easier method given below, consisting in the measurement of an air path only. If a pilot has a rule graduated to measure air-path distance in terms of time, the problem is still simpler.

SOLUTION. 1. From B draw BY in the direction 70°.

2. On BY lay off BC, a 35-minute air path. (At 120 miles an hour, air speed, the plane will travel 70 miles along the path BY in 35 minutes. $\frac{35}{60}$ of 120 = 70.) Use a time scale like that described in Problem 9, if one is available, to save computation.

3. Draw a line from C in the direction from the northwest, cutting AX at D. The pilot will be at D in 35 minutes.

Remembering the solution

Think: When the air speed is known and the ground speed is not, it is easier to measure distance by time along an air path than by miles along the track.

EXERCISE 14. Using the scales made in Exercise 13 and the scale of miles on Exercise Chart on page 297, find the time necessary to fly (*a*) 56 miles at 70 miles an hour; (*b*) 48 miles at 80 miles an hour; (*c*) 66 miles at 90 miles an hour; (*d*) 85 at 100 miles an hour.

Correcting a wrong allowance for wind drift

A pilot may have been misinformed about the wind on the start of a trip, or he may have miscalculated the correction angle. His procedure to correct the error is illustrated in Problem 11.

PROBLEM 11. Let us say that a pilot and co-pilot started on a trip from A east to P (Fig. 214) and headed their plane in the direction 70° to allow for the wind. The air speed is 90 miles an hour.

Let us say that after 20 minutes' flight they knew they should be at B but found themselves at D. What was the true wind velocity, if it remained the same during the hour, and what heading should they use for the rest of the trip, assuming the wind velocity to remain unchanged?

METHOD. In solving this problem we find the true wind vector after a given flying time as in Problem 1, then use this for the rest of the trip.

SOLUTION. 1. Draw AX to show the heading of the plane (70°) during the first portion of the trip. AX is the projected air path — the air path as of the starting time.

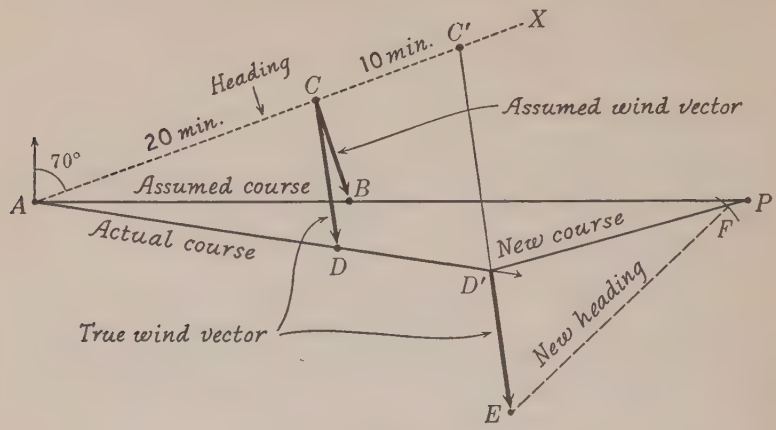


FIG. 214.

2. Lay off AC on AX the length of a 20-minute air path. If desired, draw CB, as shown, in the direction in which the wind was assumed to be. CB is the assumed wind vector for 20 minutes. B is the point on the track where the pilots should have been; but point B is not needed in the solution.

3. Draw AD. AD is the true track for the flying time (20 minutes).

4. Draw CD. CD is the true 20-minute wind vector. (A balloon that was at C at the starting time would have drifted to D during the 20 minutes.)

Suppose you are the co-pilot. While you are making the computation, have the pilot keep flying with the *same heading*. Allow yourself a reasonable time, say 10 minutes, in which to finish the problem and to determine where your plane will be at the end of that time (10 minutes). Find the heading to use after reaching that point.

5. On AX lay off 10 minutes' additional projected air path (CC').

6. Draw a line from C' parallel to CD, cutting course AD extended at D'. D' is the position at which you will be in ten minutes after leaving D.

The rest of the problem consists merely in finding a heading (Problem 2).

7. Draw $D'P$, the track for the rest of the trip.

8. From D' lay off the wind vector $D'E$ equal to CD (20-minute vector).

9. With E as center and a radius representing a 20-minute air path (30 miles), draw an arc cutting $D'P$ at F. EF is the heading for the rest of the trip. (It is the trail for the next 20 minutes.)

The pilot must stay on his course until the ten minutes have elapsed in order to reach D', then take the new heading.

Remembering the solution

To correct for an error in the wind-correction angle, draw the projected air path (heading) for the time flown, and find the true wind vector by drawing a line from the end of the projected air path (C) to the fix (D).

Allow figuring time, and recompute the heading as of the point where the pilot will be on the same course after a given time allowance.

Exercise 15. A pilot and co-pilot took off at Fort (heading toward Eden) to fly to Eden, assuming no wind to be blowing. After flying with a constant heading for 40 minutes at 90 miles an hour air speed, the pilots found themselves at Berg. They thereupon concluded that a wind had been blowing steadily during the 40 minutes. If they continued with the same heading for 5 minutes to a point B', what heading should they then take in order to fly from B' to Eden?

Effect of a shift of wind velocity

A plane is flying with a heading in the direction of AB in Figure 215, and during the flight the wind is blowing as shown by one-hour vector AW. While traveling the one-hour air path AC the plane drifts to D, and hence it travels the track AD.

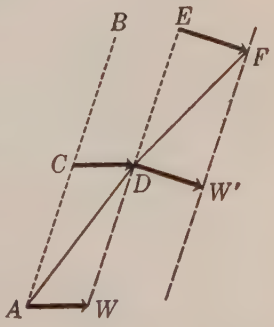


Fig. 215.

Let us say that when the plane reaches D the wind suddenly changes to a velocity represented by vector DW'. The plane continues with the same heading WE, but during the next hour, while traveling the one-hour air path DE, the plane drifts the distance EF and hence reaches F. During the second hour it travels the track DF.

In general, a shift in wind speed or wind direction will alter the course of a plane even though it keeps the same heading.

Correcting for a shift in wind velocity at an unknown time

A pilot may set out with the correct heading for the wind and experience a wind shift later without knowing the time of its occurrence. This gives rise to a problem like the one that follows.

PROBLEM 12. Let us assume that two pilots set out to fly east from A to point P with an air speed of 100 miles an hour, and that 70° was the correct heading at the time of starting. After flying with the heading AX for half an hour the pilots find themselves at D, as shown in Figure 216, and decide that the wind has shifted at some time during

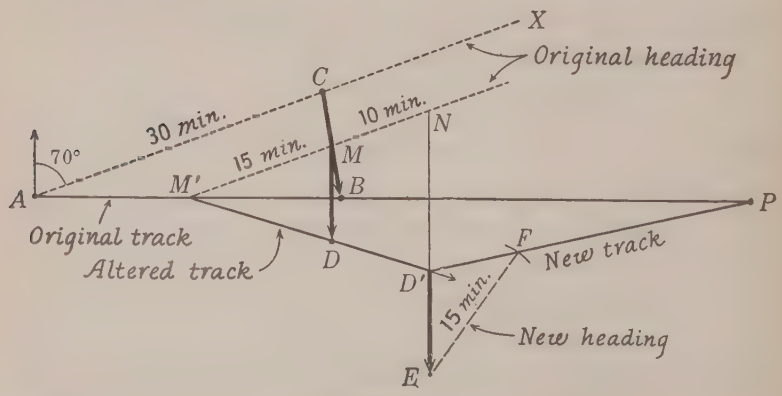


FIG. 216.

the journey. What should the pilots assume the wind velocity to be at the time of arriving at D, and what should the heading be for the rest of the journey?

METHOD. Since the pilots have no idea when the wind shifted, they assumed it most probable that the shift occurred at the half-way point in time — one-quarter hour after leaving A.

SOLUTION. First draw the wind-drift triangle the way it was assumed to be for the flying time — half an hour.

1. Draw AX (70°) to show the heading at the start.

2. Lay off AC on AX to represent the air flight (50 miles) for the flying time (half an hour).

3. From C draw CB, the assumed wind vector for the flying time (half an hour). Draw it in the direction the wind was blowing at the start.

4. Find the midpoint M of total wind vector CB. Find the midpoint M' of the track AB. We assume that a balloon at C would have drifted to B in the flying time (half an hour) if the wind had not shifted. And if the wind shifted in one half that time ($\frac{1}{4}$ hour), it shifted when the balloon was at M and when the pilots were at M' on the right track.

5. Draw MD and $M'D$. We assume that $M'D$ is the altered track after the wind shift. $M'M$ is the heading during the second half of the flying time (the same as the heading AC).

If $M'M$ is the heading and $M'D$ is the track for the second half of the flying time, MD must represent the movement of the air during that time; that is, MD is the wind vector for the second quarter hour. We assume that the wind will not change again.

6. Extend revised course $M'D$ in order to find a point D' where the plane will be after a given allowance of time (say 10 minutes). Lay off 10 minutes' additional air path MN as shown. Draw a line from N parallel to MD, cutting the course $M'D$ at D'. The plane will be at D' in ten minutes.

7. From D' lay off a quarter-hour wind vector $D'E$, equal to and parallel to MD.

8. Draw $D'P$. With E as center and a radius representing a quarter-hour air path (equal to $M'M$), draw an arc cutting $D'P$ at F. EF is the new heading.

Remembering the solution

To allow for a shift of the wind at an unknown time, (1) assume that the wind shifted at the halfway point in time; (2) draw the assumed wind-drift triangle for the flying time; (3) find the probable breaking points of the wind vector and the track (midpoints M and M'). (4) With these points and the point (D), at which the pilot finds himself, construct a new wind-drift triangle and thus obtain a new wind vector. (5) Use that wind vector for the rest of the trip.

EXERCISE 16. A pilot took off from Alfa to fly a course over Dale to an airport D 100 miles beyond Dale. He took a heading based on a wind from 250° at 20 miles an hour. After flying at an air speed of 120 miles an hour for 45 minutes, he found himself at Cape. He assumed that the original calculation of heading was correct, and he had no idea when the wind had shifted. If he continued to hold his heading for 8 minutes more, going from Cape to a point C, what heading should he adopt to fly from C straight to D?

Assuming a time of wind drift

If the pilot has reason to think that the wind shift occurred at a particular time other than the halfway point, he may plan his solution accordingly. Thus, if he suspects that the shift came after two thirds of the flying time had elapsed, he merely places M and M' two thirds of the way along CB and AB instead of at the midpoints. The solution is otherwise the same, but the pilot must be careful to remember the length of time for which MD is the wind vector.

Questions

1. How many feet are there in a statute mile? in a nautical mile?
2. A nautical mile is about how many times as long as a statute mile?
3. What is a knot?
4. Explain the expression: Constant bearing means collision.
5. Is it possible to find the time necessary to go from A to B by measuring on a chart, without finding how far B is from A?
6. Is it possible to correct for a miscalculation of wind-drift angle? If so, under what conditions?
7. What effect does a shift of wind velocity have upon the track of a plane, if the pilot holds the same heading?

Luscombe Airplane Corporation

Fig. 217. A two-float seaplane taxiing on the bay at Hamilton, Bermuda. (See also Fig. 155.)

25

RADIUS OF ACTION

A PILOT has a light plane that cruises at 100 miles an hour on 4 gallons of gasoline to the hour, and the tank holds 16 gallons. How far can the plane fly on a tankful of gasoline?

At 4 gallons an hour, 16 gallons should carry the plane for 4 hours. But we cannot afford to take a chance of running out of gasoline; so let us say that it can be flown safely for 3 hours — $3 \times 100 = 300$ miles. This distance which the pilot can safely fly we might call the *safe cruising radius* of the plane.

Area of flight

If the plane leaves point O with a tankful of gas, within what area may it fly safely?

If the air is calm, the plane can fly safely to any point within a radius of 300 miles of O, as shown in Figure 218. This circle we may call the *area of flight.*

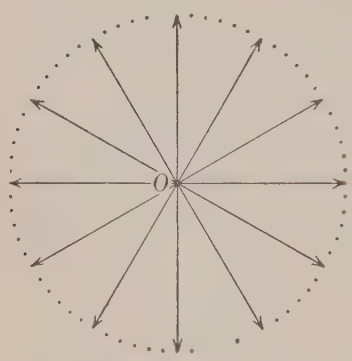


FIG. 218.

But let us suppose that the wind is blowing toward the east at 20 miles an hour. What is the area of flight of the plane in that case?

In Figure 219, OWP is a wind-drift triangle in which OW is the wind vector, WP the air path, and OP the course. Since the air path is the same

for 3 hours' flight in any direction from the starting point and equals 300 miles in this case, we know that WP is 300 miles for flight in any direction.

It follows that the area of flight from point O, in a wind shown by vector OW, is a circle with W as its center and with a radius of 300 miles, as shown.

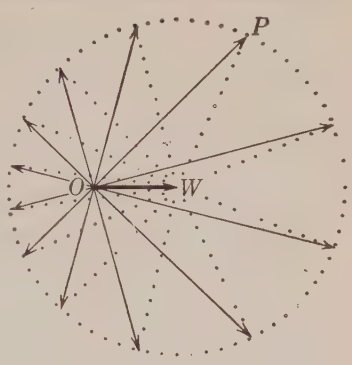


FIG. 219.

Figure 219 shows clearly how a pilot can fly farther downwind than upwind, and how the distance he can fly increases as he goes from straight upwind to straight downwind.

To find the area of flight of the plane for a 20-mile wind, as mentioned above, we would merely make OW 20 units long, then draw the circle with W as center.

EXERCISE 1. Draw the area of flight of a plane taking off from a point A with an air speed of 100 miles an hour in a north wind blowing at 40 miles an hour, assuming the safe flying time to be $3\frac{1}{2}$ hours.

EXERCISE 2. In about what directions of flight in Exercise 1 is the cruising radius just half the cruising radius toward the south? What per cent greater or less than the air speed is the maximum cruising radius? What per cent of the air speed is the minimum cruising radius?

Landing area

A pilot must realize that the distance to which he can glide from a given point is also affected by wind direction and speed.

For example, a pilot is flying over point O at a height of 5000 feet and because of motor failure must make an emergency landing. Let us say that from 5000 feet he can glide

7 miles and can remain aloft 7 minutes. What is the area within which he may land?

Of course, if there is no wind, he can land anywhere within 7 miles of A; but if the wind is blowing, say 20 miles an hour, the plane will be blown in the direction of the wind for a distance of $\frac{7}{60}$ of 20 miles, or $2\frac{1}{3}$ miles.

Hence if the wind is blowing in the direction OW (Fig. 219) and can blow from O to W in 7 minutes (the time the plane can remain aloft), the pilot must land somewhere within the circle whose center is W and whose radius is 7 miles.

We must remember in an emergency that we can glide much farther downwind than upwind; however, we must remember also that a final turn must be made in order to land upwind.

Relative wind angle

The angle which the course of a plane makes with the direction toward which the wind is blowing is the *relative wind angle.* Thus, if the course is to the north and the wind is blowing toward the northeast or the northwest, the relative wind angle is 45°. If the wind is toward the east or the west, the relative wind angle is 90°, etc.

Relation of ground speed to air speed for various relative wind angles

It is worth while to appreciate the relation of ground speed to air speed for various relative wind angles. Figure 220 shows this relation.

In Figure 220, OWP is a wind-drift triangle, in which OP is the course, OW the wind vector for one hour, and WP the air path for one hour. The line OP therefore is the track for one hour, and hence shows by its length the ground speed in the direction OP. Since OP is longer than WP, we see

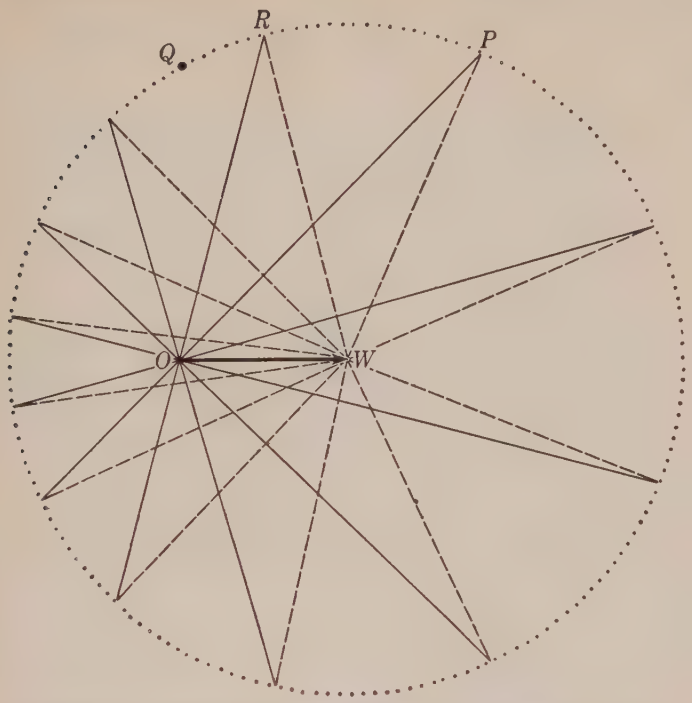


FIG. 220. The relation of ground speed to air speed at various relative wind angles.

that the ground speed exceeds the air speed for that relative wind angle. In this case the relative wind angle *POW* is 45°.

We see from the figure that the more nearly upwind we fly the less the ground speed, and the more nearly downwind we fly the greater the ground speed.

Wind at right angles

It is interesting to note that the ground speed does not equal the air speed for a course with the wind at right angles. A track *OQ* with the wind at 90° would be shorter than the air path *WQ* necessary to make good the course *OQ*.

The plane must fly partially downwind — in a direction OR — in order to have a ground speed (OR) equal to the air speed (WR).

The longer OW is, the farther OR is from being perpendicular to OW. Hence the greater the wind velocity the farther downwind the course must be to get a ground speed equal to the air speed.

Relation of heading to relative wind angle

Figure 221 shows the headings for flying in various directions from O when the wind is represented by vector OW. The angle at the end of each course line from O shows the size of the wind-correction angle for that course and a wind vector OW.[1]

The important fact to be remembered is that the correction angle is greatest when the wind and the course are 90° apart.

Also the correction angle is the same for a relative wind angle of 90° + 10°, as for 90° − 10°; the same for 90° + 20°, as for 90° − 20°; and so on.

Variation of wind-correction angle with relative wind angle

Figure 222 shows in a graphic manner the relation between the necessary correction angle and the relative wind angle. It is drawn for the case in which the wind speed is just one quarter of the air speed of the plane.

Each point on the curve shows by its horizontal position the relative wind angle, and the height of the point shows the necessary correction angle for that relative wind angle — that is, when the wind speed is just one quarter of the air

[1] The short sides of the angles do not point to W, as you might expect. To find the heading for each course, a separate wind-drift triangle was solved. The heading for the course OP', for example, is the direction of WP in Figure 220. But P' is not the same point as P (P is on a circle with W as the center).

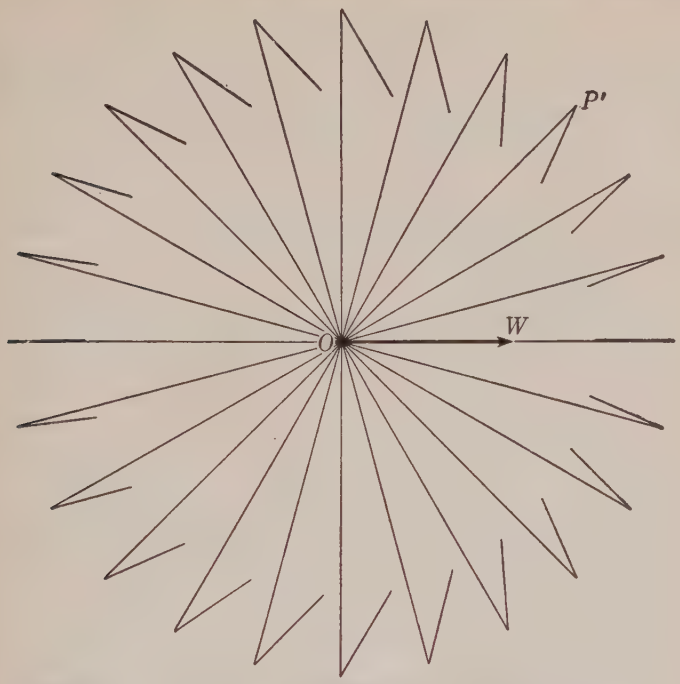


FIG. 221. The relation of heading to relative wind angle.

speed of the plane. You would get the same drift angle for a 200-mile air speed and a 50-mile wind as for a 100-mile air speed and a 25-mile wind. It is only the ratio of the two that matters. The graph for any other ratio of wind speed to air speed would be similar to this graph — symmetrical but taller for higher ratios.

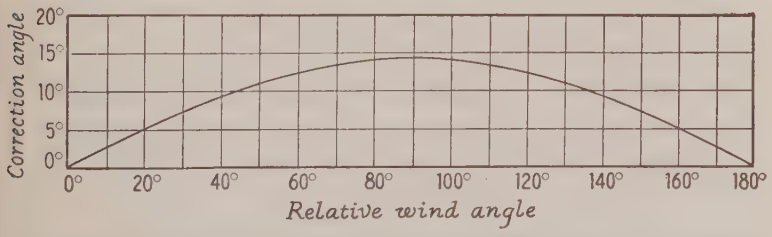


FIG. 222. Variation of wind-correction angle with relative wind angle.

Again, in this figure we see that the necessary wind-correction angle is greatest when the wind is at an angle of 90° with the desired course; that the correction angle diminishes (slowly at first) as the *relative wind angle* diminishes or increases from 90°.

Finding the headings and ground speeds for a round trip

If it is proposed to make a round trip, as from A to B and return, it is customary to find the heading and the ground speed for both the trip out and the return trip in the same drawing, as illustrated in Problem 1.

PROBLEM 1. Choose any track, air speed, and wind velocity, and determine the heading and ground speed for the trip out and the trip back, using the same wind vector.

SOLUTION. 1. Draw a line CAB as shown in Figure 223, AB representing the direction of B from A, and AC representing the direction of A from B.

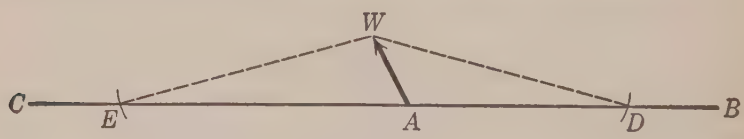


FIG. 223.

2. Draw the wind vector AW, as shown.

3. With W as center and a radius equal to the air speed, draw arcs cutting AB at D and AC at E.

4. Draw WD and WE. Triangle AWD is the wind-drift triangle for the trip out. Hence WD is the heading for the trip out, and the length of AD shows the ground speed for the trip out. Triangle AWE is the wind-drift triangle for the trip back. Hence WE is the heading for the trip back, and AE shows the ground speed for the trip back. The two ground speeds are often called the *ground speed out* and the *ground speed in.*

Remembering the solution

You might think of WD and WE as the smoke trails of two planes which left A at the same time and traveled courses AB and AC in opposite directions for one hour.

EXERCISE 3. Assuming a 25-mile wind from 240°, and an air speed of 90 miles an hour, find the heading and the ground speed in each direction in the same figure for flying a round trip (*a*) between Alfa and Eden (Exercise Chart, page 297); (*b*) between Berg and Cape; (*c*) between Fort and Cape

Safe flying time

As explained in connection with the safe cruising radius, a pilot never keeps on flying till his fuel is exhausted. A plane may carry fuel enough for 5 hours' flying, but the pilot may consider that under ordinary conditions he should allow a margin of one hour's supply of fuel. In that case he would consider that he could fly safely for 4 hours. The extra hour's supply would be reserved because he might get lost and lose time finding his way; or the airport where the pilot intended to land might be closed for some reason; or some of the fuel might leak away. (Airline planes are required to carry enough fuel to fly to the destination, then to a predetermined alternative airport, and still have fuel enough for 45 minutes' flying.)

In the above case, the pilot would call 4 hours the plane's *safe flying time.*

Radius of action

We have already investigated the distances to which a plane can fly with the wind at various angles, and have found how the plane can fly farther with a helping wind than with a hindering wind.

But when we consider the possibility of round-trip excursions in the various directions, the problem is quite different, because there is almost always a helping wind in one way and a hindering wind in the other.

Since the trip with the hindering wind takes longer than the trip with the helping wind, we are hindered longer than we are helped; and, therefore, *it always takes longer* to make any round trip with wind than with no wind. How much longer depends on the direction and the speed of the wind.

The distance *away from an airport* that a plane can fly in a given direction with a given wind velocity and still be able to get back to the airport in a given total flying time is called the *radius of action* of the plane for those conditions. When using the term "radius of action," we usually have in mind the total *safe flying time* during which the plane can remain aloft with the fuel it can carry.

The term "radius of action" is used also when the plane "returns" not to the starting point but to a second airport.

Radius-of-action problems

You can best understand the solution of a radius-of-action problem if we present first the simple problem of returning to a second airport with no wind.

PROBLEM 2. A pilot flies a plane whose safe flying time is 4 hours. How far can he fly northeast from airport A in Figure 224 and return to airport B, when no wind is blowing, the air speed being 100 miles an hour?

SOLUTION. 1. From point A draw AX to represent northeast.

2. On AX lay off AC to represent the total safe cruising radius (4×100 or 400 units).

3. Draw BC, find its midpoint M, and from M draw a line perpendicular to BC cutting AC at D. D is the point to which the plane can fly in the direction AX and return to B in 4 hours. AD is the radius of action in this case.

4. Draw DB. DB is the track from D to B.

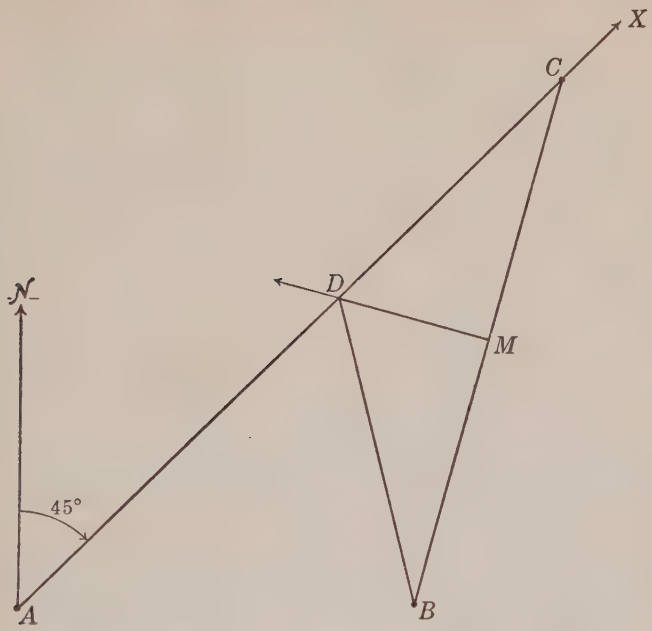


FIG. 224. The radius of action for return to a second airport, without wind.

Proof of the solution

In geometry we learn that any point on the perpendicular bisector of a line is equidistant from the ends of the line. This shows that $DB = DC$. Hence $AD + DB = 400$ miles.

Remembering the solution

Think: I must bend the total straight track AC at some point D so that point C swings around to point B, as shown in Figure 225. And D has to be equidistant from B and C.

Drawing a perpendicular bisector

A quick and easy way to draw a perpendicular bisector of a line BC is shown in Figure 226. With B and C as centers and any radius more than half the length of BC,

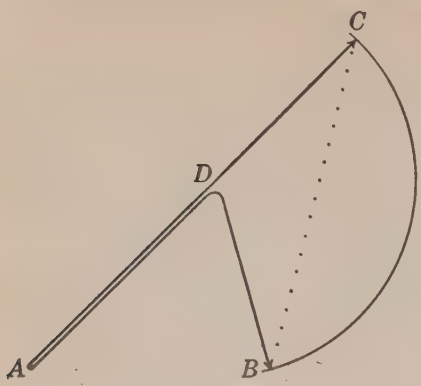


FIG. 225.

FIG. 226.

draw two intersecting arcs. Draw a line through the two points of intersection of the arcs. The line is the perpendicular bisector of the line BC.

EXERCISE 4. A pilot took off from Eden (Exercise Chart, page 297) to fly in the direction of Alfa, planning to return to Berg. What is his radius of action in the direction of Alfa if there is no wind blowing, assuming the air speed to be 80 miles an hour and the flying time to be (*a*) $1\frac{1}{2}$ hours? (*b*) $2\frac{1}{4}$ hours? (*c*) 3 hours? What is the heading for the return trip in each case?

Area of action

We might investigate the total area within which a plane can fly from A and return to B. This we might call the area of action for a trip beginning at A and ending at B.

If we look at Figure 224 we realize that we merely found the point D on AX, the position of D being such that the total distance ADB was 400 miles; in other words, the sum of the distances DA and DB was 400 miles.

The path of any point P moving around fixed points A and B so that the sum of the distances from P to A and B is constant is an ellipse (Fig. 227). The total distance

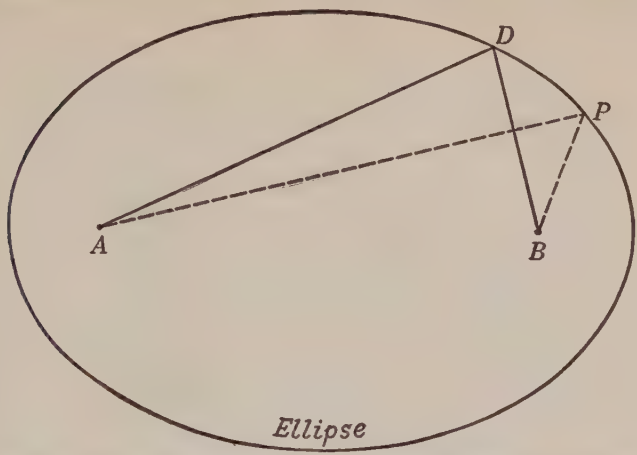


FIG. 227. The area of action when a plane returns to a second airport, without wind.

APB is the same for all positions of P on the ellipse. Points A and B are the *foci* of the ellipse. Each one is a *focus*.

Drawing an ellipse

A convenient method of drawing an ellipse is illustrated in Problem 3.

PROBLEM 3. Draw an ellipse to show the area of action of a plane flying in calm air from A to P and back to B, as in Figure 227, if the total distance flown is 400 miles, A and B being 300 miles apart.

SOLUTION. 1. Place the sheet of paper on a drawing board and stick pins at A and B, as shown in Figure 228.

2. Find a point C on AB extended, C being so located that $CA + CB = 400$ units. BC must equal 50 units in this case; then $AB + BC + CB = 300 + 50 + 50 = 400$ units. That is, $BC =$ one half of $400 - 300 = \frac{1}{2}$ of $100 = 50$.

3. With a pencil point at C and a thread looped around the pencil point and arranged past the pins as shown in the middle drawing, swing the pencil around to make the first half of the ellipse as shown.

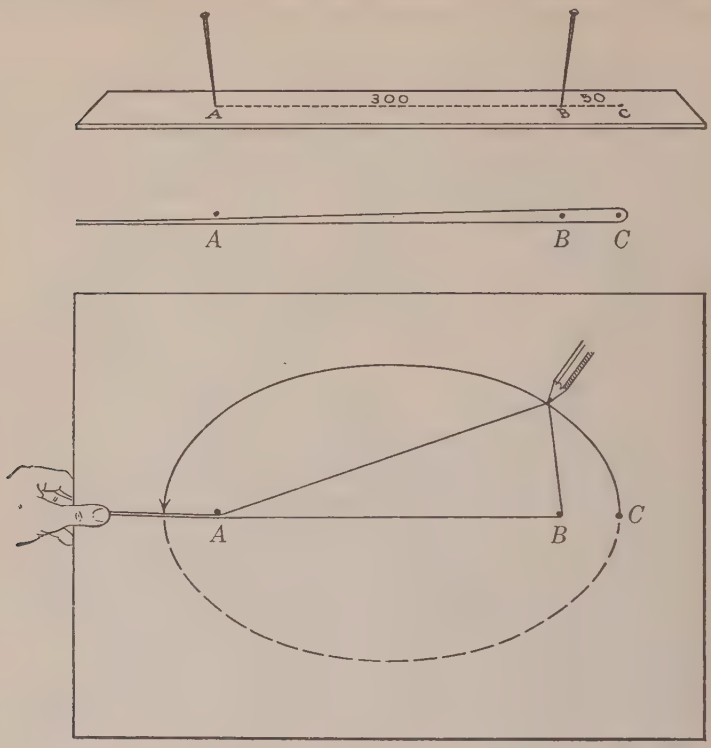


FIG. 228. The drawing of an ellipse.

4. Place the threads on the other side of pin A; and, beginning again at C, draw the other half of the ellipse. The ellipse represents the *area of action* of a plane starting from A and returning to B 300 miles away after a 400-mile flight in calm air.

EXERCISE 5. Draw the area of action of a plane leaving Alfa and returning to Berg, the air speed being 80 miles an hour and the flight time $1\frac{1}{2}$ hr. Assume there is no wind.

Radius of action from an airplane carrier

There are vessels from which a number of airplanes can fly and return, landing directly on the vessel. Such a vessel is called an *aircraft carrier*. (See Fig. 229.)

FIG. 229. The United States Navy aircraft carrier *Lexington*. Such a vessel is essentially a landing field that moves along with the fleet.

PROBLEM 4. An aircraft carrier is steaming toward the northwest at 25 miles an hour. If a plane with an air speed of 150 miles an hour sets out from the carrier to scout in a direction due west with no wind blowing, how far can it go in that direction and return to the carrier in 3 hours; that is, what is the radius of action under those conditions? What is the heading for the return trip?

SOLUTION. 1. Draw AB, the path of 3 hours' motion of the vessel (75 units, Fig. 230).

2. Draw AC, the total distance the plane can fly toward the west in 3 hours (450 units).

3. Draw BC. Draw the perpendicular bisector of BC intersecting AC at D. AD is the radius of action. AD represents 250 miles.

4. Draw DB, the track and the heading for the return trip. Angle $ADB = 15°$. Hence the heading $= 90° - 15° = 75°$.

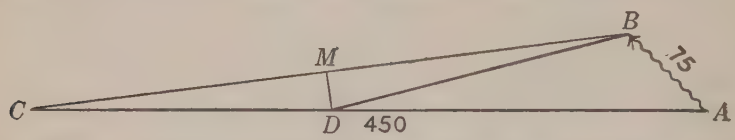


FIG. 230. The radius of action from an airplane carrier, without wind.

Remembering the solution

Think: I can draw the total track of the plane in a straight line, then bend it back to the position of the carrier at the time the pilot is due to land on it. I must bend it back at such a point that the return trip just equals the rest of the straight trip. I can find the place to bend it with a perpendicular bisector.

EXERCISE 6. An aircraft carrier is steaming toward 300° at 25 miles an hour. Assuming that there is no wind, what is the radius of action of a plane of 150-miles-an-hour air speed and 3-hour flying time scouting a course in the direction (*a*) 10°? (*b*) 250°? What is the heading for the return trip in each case?

Radius of action with the wind blowing

We are now ready to find the radius of action of a plane with return to the starting point, with wind blowing.

PROBLEM 5. Find the radius of action of a plane starting northeast, if the air speed is 100 miles an hour, the flight time is 4 hours, and the wind is blowing from the east at 25 miles an hour. (How long can the plane fly northeast and how far?) What are the headings out and back?

SOLUTION. 1. Draw a line AX to represent the course of the plane to the northeast (Fig. 231).

2. Draw AW, the wind vector for the total time (4×25 miles $= 100$ miles).

3. With W as center and a radius representing the length of a 4-hour air path, draw an arc cutting AX at B. (Radius represents 4×100 miles, or 400 miles.)

4. Draw WB. WB is the heading for the trip out. WB would represent the total air path (smoke trail) if the trip were all in a straight line.

In this case we want the trip to end at A; so we must bend the air path WB at a point D so that it goes back to A.

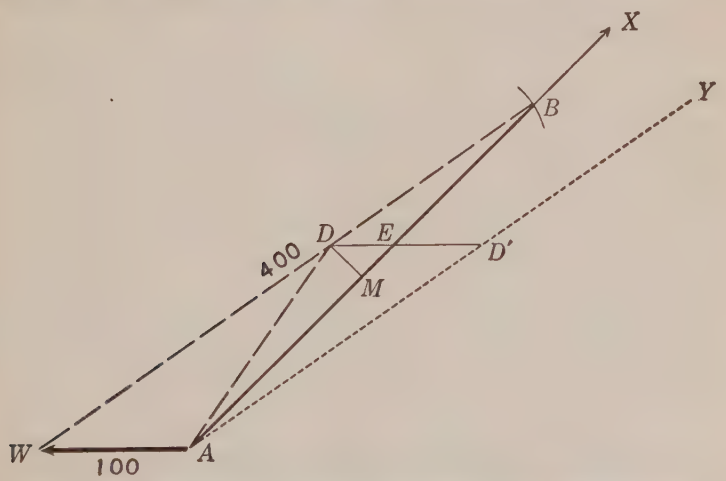


FIG. 231. The radius of action for return to the same airport, with the wind blowing.

5. Draw the perpendicular bisector of AB, cutting WB at D. WD is the air distance the plane can fly before needing to return to A. Measure WD and divide its length by the air speed (100) to find the number of hours the plane can fly away from A (the *flying-out time*).

6. Draw a line DE parallel with WA as shown. AB is the track of the plane, and E is the point on the track to which the plane can fly. AE is the radius of action in this case. While the plane has flown an air distance and direction WD, it has actually flown AE on the track.

WB is the smoke trail the plane would have left if it had flown from A to B. WDA is the actual air path (smoke trail) of the plane as of the time of arrival at A.

Perhaps you will prefer to draw a line AY parallel to WB to represent the heading when flying from A. Then you will see that when flying an air distance and direction AD' (which is the same air distance and direction as WD), the plane will have drifted $D'E$ and be at E.

Measure AE to scale to find the distance out, which the plane can fly. AE is the *radius of action.*

7. Draw DA. DA is the heading for the return trip.

Remembering the solution

Think: I must first find the smoke trail the plane would make if it flew the required course in one direction for the full time. Then I must bend the trail back to the point to which the plane returns. Remember the perpendicular bisector method of finding the bending point of the trail.

Remember that it is the trail (air path) which we bend, and that the actual point of turning back is on the track. To find the turning point on the track, think — where did the smoke at the point of bending of the trail blow from? Of course it came from directly upwind.

Exercise 7. A pilot took off from Fort to fly in the direction of Dale with the wind blowing from 265° at 24 miles an hour. What is his radius of action under the following

conditions, assuming the return trip made to Fort (page 297)? How long can the pilot fly in the direction of Dale in each case and what is his heading in each direction?

(*a*) Air speed 100 miles an hour; flying time $1\frac{3}{4}$ hours
(*b*) Air speed 80 miles an hour; flying time $2\frac{3}{4}$ hours

Formula method

It is possible to solve a radius-of-action problem (when the return is made to the starting point) by means of the following formula:

$$\text{Radius of action} = \text{Total flying time} \times \frac{(\text{Ground speed out}) \times (\text{Ground speed in})}{(\text{Ground speed out}) + (\text{Ground speed in})}$$

PROBLEM 6. A pilot wishes to fly as far east from airport *A* as possible and get back to the same airport in 3 hours. There is a southeast wind blowing at 20 miles an hour. Find the distance east from the airport (radius of action) which he can fly, and the heading for the return trip. Assume an air speed of 90 miles an hour. Use the formula.

SOLUTION. 1. By means of a drawing as in Problem 1 find the ground speed out and the ground speed in (Fig. 232). Let us assume the ground speed out is 74 miles an hour and the ground speed in is 103 miles an hour.

2. Substitute these values in the formula.

$$\begin{aligned}\text{Radius of action} &= 3 \times \frac{74 \times 103}{74 + 103}\\ &= 3 \times \frac{7622}{177}\\ &= 3 \times 43 \text{ miles}\\ &= 129 \text{ miles}\end{aligned}$$

3. Find the heading for the return trip from Figure 232. The heading is the direction *WC*.

FIG. 232.

In solving radius-of-action problems, such as Problem 5, you may use whichever method you prefer.

EXERCISE 8. Find the radius of action in Exercise 7 (*a*) and (*b*) by means of the formula. Compare your results by the two methods.

Derivation of the formula

If you are interested in the manner in which the formula was obtained, read the following explanation:

Suppose we let g stand for the ground speed out, and s for the ground speed in.

1. Then, if the trip out takes one hour, the trip back will take $\frac{g}{s}$ of an hour. (Think: If the ground speed out is 60 miles an hour and the ground speed in is 120 miles an hour, the trip back takes only $\frac{60}{120}$ as long as the trip out.)

2. Hence the round trip takes $1 + \frac{g}{s}$ hours. This means that if the total flying time is $1 + \frac{g}{s}$ hours, the radius of action $= g$ (the distance out in one hour).

3. Now for simplicity let the total time $1 + \frac{g}{s}$ hours be represented by T.

If in T hours' total time the radius of action is g, in 1 hour's total time the radius of action $= \frac{1}{T}$ of g. (The radius of action is in proportion to the total time.)

4. Substituting the more complicated value $1 + \frac{g}{s}$ for T, we find that in one hour's total time, the radius of action $= \frac{1}{1 + \frac{g}{s}}$ of g, or $\frac{g}{1 + \frac{g}{s}}$.

Multiplying both numerator and denominator by s:

$$\frac{g}{1 + \frac{g}{s}} = \frac{sg}{s + g}, \quad \text{or} \quad \frac{gs}{g + s}, \text{ hence}$$

$$\left.\begin{array}{l}\text{Radius of action for}\\ \text{one hour total time}\end{array}\right\} = \frac{(\text{Ground speed out}) \times (\text{Ground speed in})}{(\text{Ground speed out}) + (\text{Ground speed in})}$$

Remember that the radius of action is in proportion to the total flying time; that is, for 3 hours' total flying time you can go just 3 times as far as when the total flying time is one hour. Hence (abbreviating the ground speeds) —

$$\text{Radius of action} = \text{Total flying time} \times \frac{GSO \times GSI}{GSO + GSI}$$

Radius of action varies with varying conditions of wind

Computations show that the radius of action of a plane of given air speed and safe flying time (for return to the same airport) varies in that the greater the ratio of the wind speed to the air speed of the plane the shorter the radius of action.

Table of radius values

Table 12 shows the relative values of the radius of action for various wind conditions.

It shows that when the speed of the wind is 25 per cent of the air speed of the plane and the wind is at 90° to the

TABLE 12

RADIUS OF ACTION VALUES AS PER CENTS OF THE NO-WIND RADIUS FOR VARIOUS RATIOS OF WIND SPEED TO AIR SPEED, AND FOR VARIOUS ANGLES OF RELATIVE WIND

WIND RATIO TO AIR SPEED	90°	45° OR 135°	0° OR 180°
0°	100%	100%	100%
25°	94%	95%	97%
50°	75%	80%	87%
75°	44%	52%	66%
100°	0%	0%	0%

track (right or left), the radius of action of the plane is 94 per cent of what it would be without wind. It is 95 per cent of the no-wind radius for a wind at 45° or 135° to the track (right or left); and it is 97 per cent of the no-wind radius when the wind is a straight head wind or tail wind (0° or 180°).

With a wind speed 50 per cent as great as the air speed the radius values are much less, and so on.

The lesson to be learned is that (1) for wind velocity up to one quarter of the air speed the radius of action in any direction is about $\frac{19}{20}$ of the no-wind radius of action; but that (2) as the wind velocity increases above 25 per cent of the air speed the radius decreases faster and faster; and (3) that the radius for directions at right angles to the wind is greater than with the wind and against it.

If the wind were blowing 100 per cent as fast as the air speed, you could not fly in any direction and return to the starting point! You could not even start to fly upwind, and if you flew downwind you could not get back.

Returning to a second airport

Let us now solve a problem similar to Problem 5, with the wind blowing but with the return trip made to a second airport, as in Problem 2.

PROBLEM 7. If a plane has an air speed of 200 miles an hour and the wind is blowing at 50 miles an hour from the north, what is the radius of action of the plane flying west from airport A and returning to airport A' in Figure 233 in 4 hours? What are the headings out and back, and the flying-out time?

SOLUTION. 1. Draw AX to represent the westward track of the plane.

2. Draw AW to represent the southward motion of the air for 4 hours (200 units).

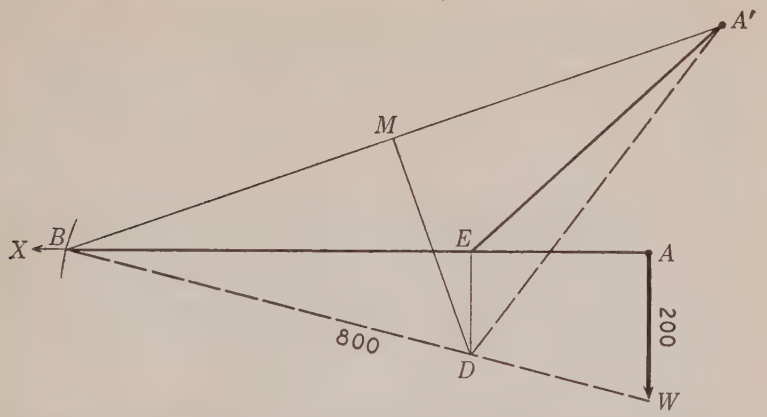


FIG. 233. The radius of action for return to a second airport, with the wind blowing.

3. With W as center and a radius representing a 4-hour air path (800 units), draw an arc cutting AX at B. Draw WB. The direction of WB is the heading on the trip out.

4. Draw BA'. Draw the perpendicular bisector of BA' cutting WB at D. Draw DA'. The direction of DA' is the heading for the trip back to A'.

5. Draw a line DE as shown parallel to WA. E is the point on the track at which the turn must be made. AE is the radius of action. EA' is the track back to A'.

6. The air distance WD divided by 200 gives the number of hours the plane can fly in going from A to E.

Remembering the solution

First we find the total air path (trail) corresponding to a total trip in the outgoing direction on the track.

Then we bend the air path at a point so located that the air path can end at the destination instead of continuing straight. A perpendicular bisector helps us to do this.

We must remember to follow the wind direction from the bend in the trail to the track, to find the actual point on the track where the plane turns back.

The time of flying out is obtained by measuring the air path out, not the track.

The only differences between this solution and that of Problem 5 are that the line to be bisected is drawn to A' instead of to A, and that the heading for the return trip is DA' instead of DA.

Exercise 9. What would the radius of action be in each case in Exercise 7 (page 378) if the return were to be made to Alfa? What is the heading in each direction and how long may the pilot fly in the direction of Dale?

Radius of action from an aircraft carrier, with wind blowing

This is similar to Problem 7. If we know where the aircraft carrier will be at the end of the flying time, that position is the same as a second airport.

Problem 8. A plane leaves an aircraft carrier at A (Fig. 234) to scout in a direction due east from A. The wind vector is as represented by AW, and 1 hour's motion of the carrier is represented by AC. The plane has an air speed of 100 miles an hour and the pilot wishes to return to the carrier in 3 hours.

Find the point at which the plane must turn back, the heading out and back, and the time out.

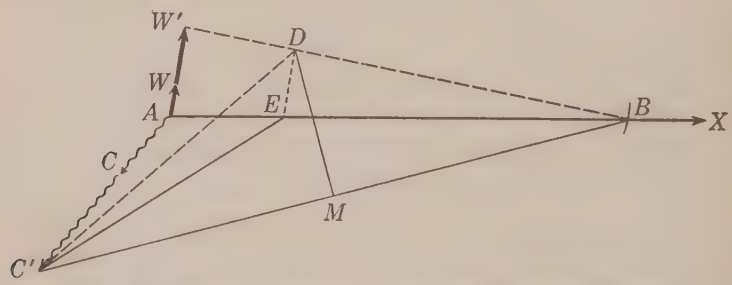


Fig. 234. The radius of action from an aircraft carrier, with the wind blowing.

SOLUTION. 1. Draw AX to represent the eastward track of the plane.

2. Extend vector AW to W', so that AW' is the wind vector for 3 hours.

3. Extend vector AC to C', so that C' is the vessel's position after 3 hours.

4. With W' as center and a radius equal to a 3-hour air path of the plane (300 miles), draw an arc cutting AX at B. Draw $W'B$. $W'B$ is the heading for the trip out.

5. Draw $C'B$. Draw its perpendicular bisector cutting $W'B$ at D. Draw DC'. DC' is the heading for the trip back.

6. Draw DE to AX parallel to $W'A$. E is the point on the course at which the plane must turn back.

7. $W'D$ is the air path out, and DC' is the air path back as of the time of arriving at C'.

Measure $W'D$, and divide its length by the air speed to find the flying-out time.

8. Measure AE to find the distance flown out. EC' is the track from E back to C', the position of the ship at the end of the 3 hours.[1]

EXERCISE 10. An airplane carrier is steaming eastward at 24 miles an hour. A plane with an air speed of 150 miles an hour sets out to scout a course in the direction of 20°. What is its radius of action and flight time out if the wind is blowing at 30 miles an hour (*a*) from 60°? (*b*) from 340°? What is its heading in each direction? (Flight time, 3 hr.)

Scouting along a course

Problem 9 differs from the preceding problems in that the return trip rather than the trip out is to be made along a given course.

[1] It is possible to use the radius-of-action formula in solving a problem similar to Problem 8, provided we substitute for the ground speed out and the ground speed in, components of these velocities in opposite directions — the component of the ground speed out being called the *rate of departure* and the component of ground speed in being called the *rate of closing*. However, the graphic method given above is considered a quicker method and easier to understand and remember.

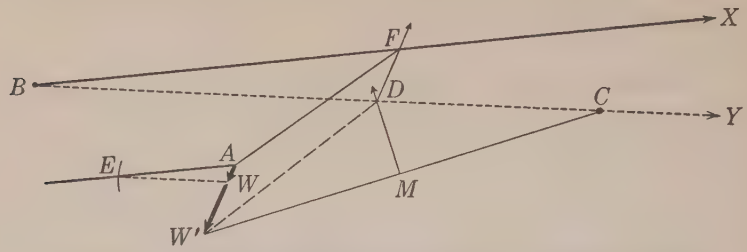


FIG. 235. The radius of action for return to a second airport, along a given course.

PROBLEM 9. A pilot on an aircraft carrier at A (Fig. 235) is ordered to scout along as much of the course BX as possible and arrive at B in 5 hours. The wind is blowing as shown by vector AW. To what point on BX shall the pilot fly, and with what heading?

SOLUTION. 1. Find the heading necessary to fly the course BX in the direction toward B. (See triangle AWE.) WE is the required heading.

2. Draw BY parallel to EW; lay off BC on BY equal to a 5-hour air path (5 × air speed). CB would be the trail of the plane if it flew for 5 hours on the course XB, arriving at B.

3. Extend AW to W', making AW' the wind vector for the 5 hours. The trail of the plane for the 5-hour trip must be drawn from W'.

4. Draw $W'C$; draw its perpendicular bisector cutting BC at D. Draw $W'D$. $W'D$ is the heading for the trip from A to the course BX.

5. Draw DF as shown, parallel to $W'A$. F is the point at which the plane will reach the course BX. AF is the track from A to the course BX.

Remembering the solution

As before, the solution consists in finding a straight air path (CB) for the total flying time in the direction of one of the required headings, then bending it so that it begins at the end of the total wind vector and ends at the destination.

EXERCISE 11. An aircraft carrier is 100 miles southwest of seaport B. A vessel is presumed to be steaming a course approaching seaport B from the west. The wind is from 0° at 40 miles an hour. A pilot whose plane has an air speed of 140 miles an hour wishes to fly from the carrier and scout along as much of the vessel's course as possible and land at B in 3 hours. What headings must he use in flying to the vessel's course and along the course, and how long will he be in getting to the course?

Flying to the "nearest airport"

A pilot sometimes loses time in a stiff head wind and decides he may not reach his destination with the fuel that is left. He decides therefore to fly to the "nearest airport." That is, he wishes to fly to the airport to which he can fly in the *least time*. Also he needs to determine this airport *promptly*. Such choice of an airport is illustrated in Problem 10.

PROBLEM 10. Let us say that a pilot is flying the eastward course from A to B, shown in Figure 236 (a). His air speed is 80 miles an hour and he is flying in a 40-mile wind from southeast.

As he approaches point P on the course, which he recognizes and knows to be 40 miles from B, he suspects that he may not be able to reach B on the remaining fuel.

There are alternate airports at C and D, and the pilot wishes to decide whether to continue on to B or to fly to C or to D. Let us say he expects to be ready to decide on reaching point P.

Which airport can he reach in the least time from P?

A pilot flying alone might have difficulty solving this problem while piloting the plane. But as a co-pilot you might need to solve such a problem.

At first glance it would appear as if the pilot could get to airport B in the least time, but the solution shows that this is not the case.

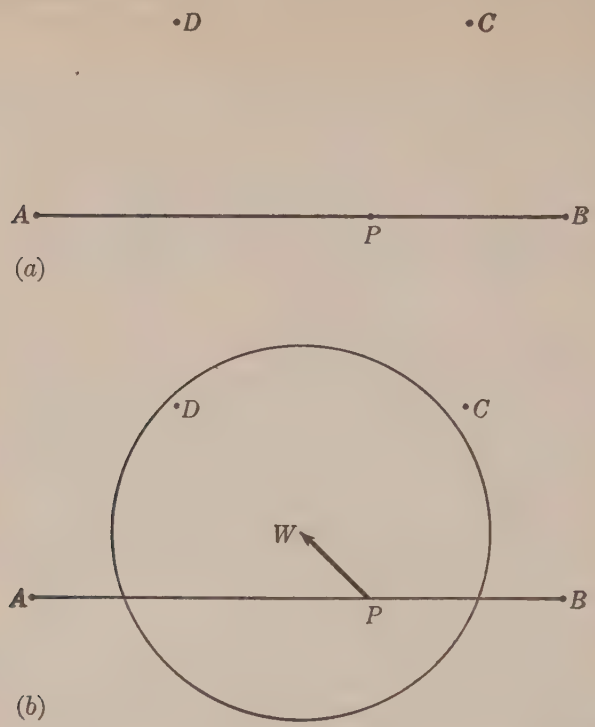


FIG. 236. A method for determining the "nearest airport," with the wind blowing.

SOLUTION. The pilot first estimates the probable length of time it will take to reach one of the airports. Let us say he decides it will take about half an hour.

1. He draws a half-hour wind vector PW as shown in Figure 236 (b).

2. With W as center and a radius representing a half-hour air path (40 miles), he draws a circle as shown in Figure 236 (b). The circle is the area of flight from P under the given wind conditions for half an hour.

Since D lies within the area of flight and B and C do not, the pilot knows that D can be reached within half an hour but B and C cannot. Hence he decides immediately to fly to airport D although it is the farthest from P.

If the circle includes two or more airports or no airport, the pilot will choose a shorter or a longer time and (1) draw a new wind vector PW' and (2) draw a new circle with W' as center, so that only one airport lies inside the circle. It is not sufficient merely to draw a larger or a smaller circle with W as center because the center of the circle changes as the radius changes.

EXERCISE 12. A pilot took off from Fort (Exercise Chart, page 297) to fly to Dale at 90 miles an hour air speed, with the wind blowing from 100° at 28 miles an hour. When halfway there the pilot decided he could not make Dale. Which airport was "nearest" him then, in point of time?

QUESTIONS

1. What is the safe cruising radius of a plane?
2. What is the area of flight of a plane?
3. What effect does a wind have on the area of flight?
4. What is a relative wind angle?
5. What is the effect of change of relative wind angle on the ground speed?
6. For what relative wind angle is the ground speed equal to the air speed?
7. Under what conditions is the ground speed least? greatest?
8. What is the effect of a change of relative wind angle on the wind-correction angle?
9. For what relative wind angle is the correction angle greatest? least?
10. If the wind speed is 25 per cent of the air speed, the correction angle necessary when the wind is at 45° to the course is about what fractional part of the correction angle necessary when the wind is 90° to the course?
11. What is meant by safe flying time?
12. What is meant by radius of action?
13. Is there any condition in which the radius of action with wind blowing equals the no-wind radius of action? Why?
14. What is meant by area of action as distinguished from area of flight?

15. Can you define an ellipse? It is the path of a point so moving that . . .
16. What is the formula for finding the radius of action when return is made to the same airport?
17. If a plane is to return to the same airport, is the radius of action greater when the wind is at right angles to the course or in line with the course?
18. What is the radius of action of a plane when the wind speed equals the air speed?

FIG. 237. A T.W.A. Stratoliner taking off from La Guardia Field, New York. This is a four-engine, 33-passenger, 250-mile-an-hour plane, which cruises at over-weather altitudes of 15,000 to 20,000 feet.

26

FLYING THE FIGURE EIGHT

ONE of the maneuvers the pilot must execute with skill and precision in a flight test for a private pilot rating is flying a figure eight around pylons. (See page 570 of Chapter 41 on pilot certification.)

There are two kinds of figure eight around pylons. One kind is the *circular eight* and the other is the *on-pylon eight.* When executing the circular eight, the pilot is expected to make a loop at each end of the eight which is the arc of a circle with the pylon at the center. In the case of the on-pylon eight, the wing is to be held pointing directly at the pylon at all times during the loop (except when going from one loop to the other).

The eight we have called the circular eight is commonly called the "eight around pylons," but this is a poor name for it because both these eights are eights around pylons and because the name does not describe the eight as distinguished from the on-pylon eight. It is considered preferable, therefore, to call it a "circular eight" to show that it has circular loops. (The on-pylon eight does not have circular loops, for reasons explained later.) The circular eight or "eight around pylons" may be of either of the shapes shown in Figure 322, page 572.

In order to fly the circular eight and make correct circular loops, it is necessary to understand what is required in the way of an air path, especially in a moderately strong wind.

The following discussion is designed to help you understand the technique of flying a figure eight.

Flying a circle with reference to the air

It is well to investigate first what kind of path over the ground is made by an airplane that is flown around in a perfect circle with reference to the air, when the wind is blowing.

It is a fairly easy matter to determine such a path, as is shown in Figure 238.

First we draw a circle, as shown at the left, to represent the circle that would be flown if the air were stationary.

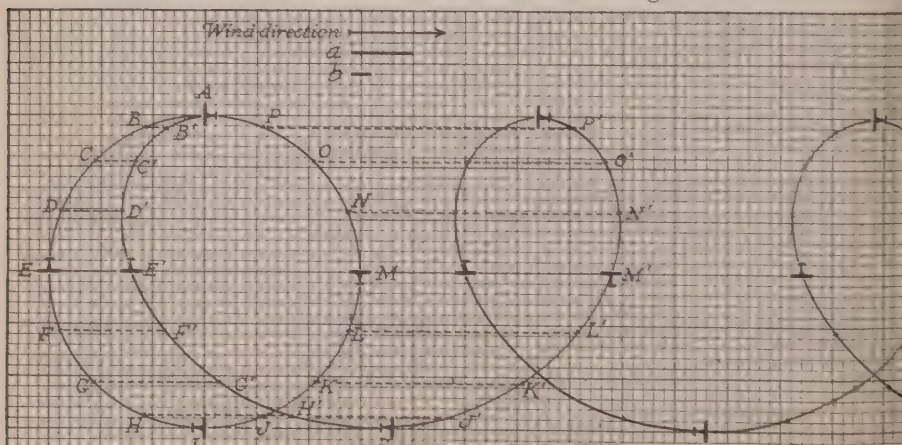
Next we divide the circle into a number of equal parts, say 16, as shown, and we consider the time necessary to fly $\frac{1}{16}$ of the circle as a unit of time (say one second).

Next we assume a given wind velocity (speed and direction). In Figure 238 we assume that the wind speed is such that while in one second the plane flies a distance *a* with reference to the air, a balloon would be blown a distance *b* by the wind.

Next we think of balloons as placed at each of the 16 division points of the circle, which let us call *A*, *B*, *C*, *D*, *E*, and so on, as shown in Figure 238.

We assume the plane to start at *A*, and we know that during the first second, while the plane is flying from

FIG. 238. The path of a plane *over the ground* when flying a circle with reference to the air, with the wind blowing.



balloon A to balloon B, balloon B will be blown to a point B' a distance b downwind from B, as shown. Hence the plane actually flies from A to B' during the first second.

And while the plane is flying from balloon A to balloon C, balloon C will be blown a distance $2\,b$ to a point C', as shown. That is, at the end of the next second the plane is at C'.

We find point D' by knowing that in three seconds balloon D will have blown from D three times b, to D', and so on.

In this way we find points A to P' and draw a smooth curve through these points.

Notice how the distance actually traveled in a second is greater when the plane is going with the wind and less when the plane is going against the wind (see tops of loops).

The amount by which the actual flight path deviates from a true circle depends, of course, upon the speed of the wind. In a light (slow) breeze the loops would be very nearly circular, but in a strong (fast) wind the loops would tighten up.

Exercise 1. Draw a figure showing the shape of the path a plane would make over the ground if it flew $1\frac{1}{2}$ times around a circle with reference to the air, clockwise, with the wind blowing toward the east two thirds as fast as the air speed of the plane. Begin at the south point of the circle.

Flying a circle with reference to the earth

We have seen what kind of path a plane makes over the ground when flying a circle in the air. It is interesting to reverse the problem and investigate the path a plane must make in the air in order to "make good" a true circle over the ground. This problem has practical application because of being related to the flying of a circular eight.

At first thought we might conclude that the second path would be merely the reverse of the first. Thus, if we stand

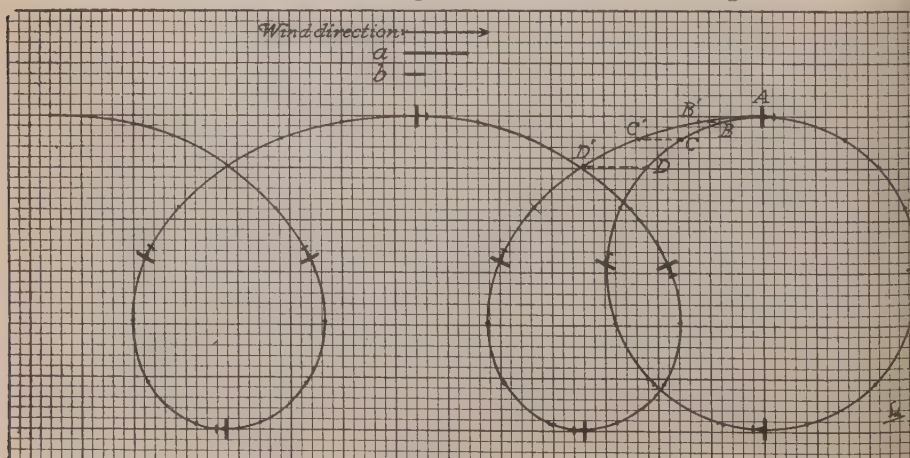
still on a flatcar moving east at 4 miles an hour, our path over the ground is east at 4 miles an hour; but in order to stay over the same spot of ground we would have merely to walk west at 4 miles an hour on the flatcar.

But investigation shows that while the second path of the plane mentioned above is very nearly a reverse of the first, the two paths differ slightly in shape.

To draw the second path we first draw a circle, as shown at the right in Figure 239, to represent the circular path of the plane we wish to make with reference to the ground. Again, as before, we suppose the speed of the wind to have a known ratio to the air speed of the plane. In Figure 239 we let a represent the distance the plane can fly with reference to the air in a second (same distance as required to traverse $\frac{1}{16}$ of the circle in Figure 238), and we let b represent the distance the air moves in a second (the same as in Figure 238). We assume the plane to begin the circle at A, and first find a point B', so located that AB' equals a and $B'B$ equals b; that is, B' is the distance b directly upwind from the circle.

Next we find a point C', so located that $B'C'$ equals a and $C'C$ equals $2\,b$; then a point D' so located that $C'D'$ equals a and $D'D$ equals $3\,b$; and so on.

FIG. 239. The path of a plane *with reference to the air* when flying a circle with reference to the ground, with the wind blowing.



The positions of B', C', D', etc., can be found by the method of "trial and error"; that is, by guessing at a position and measuring to see whether it is right. A more exact method is as follows: To find B', draw a circle equal in radius to the given circle but having its center a distance b upwind from the center of the given circle. With A as a center and a radius equal to a, draw an arc cutting the second circle. The intersection is B'. To find C', draw a circle equal in radius to the given circle but having its center a distance $2\,b$ upwind from the center of the given circle. With B' as center and a radius equal to a, draw an arc cutting the new large circle. The intersection is C'. Continue in the same manner to find D', E', etc.

Actually, when balloon B' is reached, it has been blown to B; when balloon C' is reached, it has been blown to C; and so on.

We see that in Figure 238 the several points A, B, C, D, etc., on the circle are equidistant, but in Figure 239 the points A, B, C, D, etc., on the circle are unequally spaced. The downwind part of the circle (bottom) is flown much faster than the upwind part (top).

Application to racing

In an air meet in which pilots are racing a course around pylons, a pilot not understanding the facts learned in this chapter about flying a circle sometimes makes a serious mistake in rounding a pylon, either of going too far or of cutting too short.

Let us say the pilot intends to fly the course AB around pylon P, using an arc of a circle, as shown in Figure 240.

If the turn is started downwind as shown at the left, the pilot may forget that a normal turn in the air beginning at D opposite the center C of the arc will take him around on the dotted curve DEF. (See Fig. 238.) This may cause him to swing around the curved path $ADEG$ and lose time.

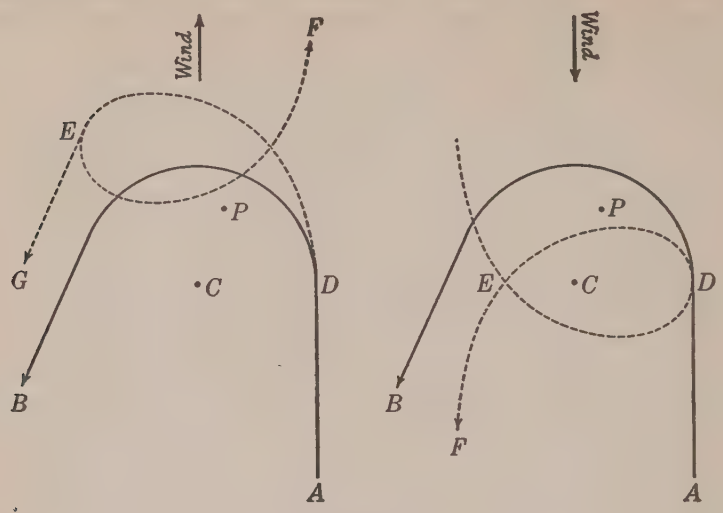


FIG. 240.

On the other hand, if the turn is started upwind as shown at the right, the pilot may forget that a normal turn in the air beginning at *D* will swing him around on the path *DEF* and he may miss the pylon altogether and be disqualified.

Flying a circular eight

Figure 241 shows the path necessary to be taken with reference to the air to execute with reference to the ground a figure eight consisting of two circles with pylons *P* and *P'* as centers.

As before, *a* represents one second's flight of the plane with reference to the air, and *b* represents one second's motion of the air with reference to the ground. The large loops show the air path of the plane in executing the figure eight, once around.

The plane starts the eight at *A*, downwind, first executing the circle on its left (top circle in the figure), then the circle on its right. Note the following conditions.

(1) The plane must be banked steeply at the start, because the curve $A'B'C'D'$ made in the air is a sharper curve than the portion $ABCD$ of the circle.

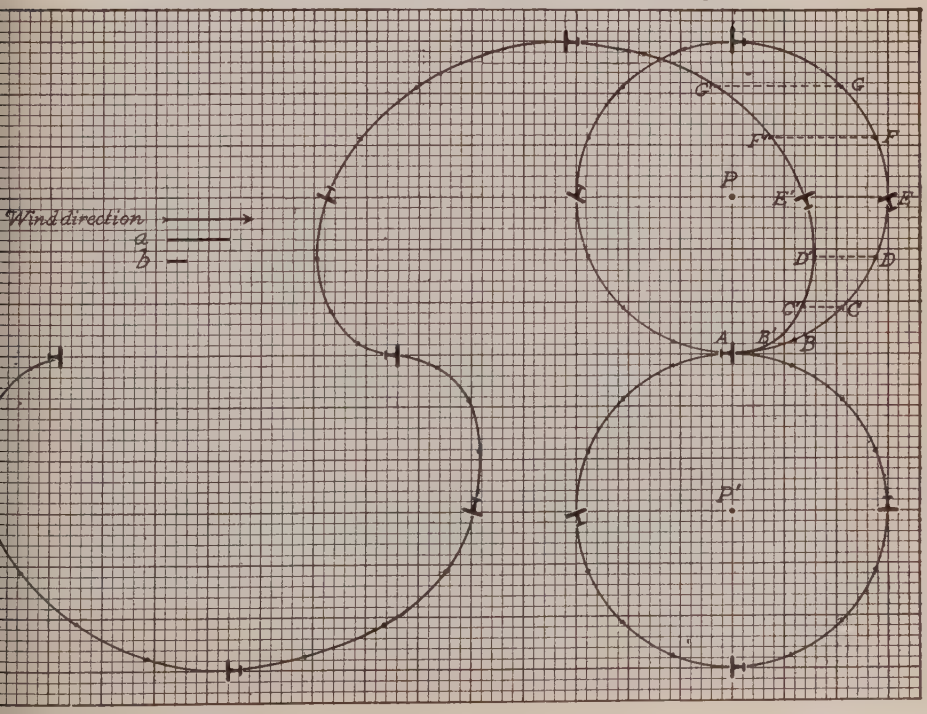
(2) When one quarter of the way around the first circle, the plane is not headed in the direction in which it is moving. (If the plane started toward the east at A, when it gets one quarter of the way around the circle it is moving north but heading west of north, as shown at E'.)

(3) Beyond this first quarter point and up to about the three-quarter point the plane is flying a curve with reference to the air that is more nearly straight than the arc of the circle, and it requires less banking than otherwise.

(4) The travel around the second and third quarters of the circle is slower than around the first and fourth quarters.

(5) At the three-quarter point the plane is traveling south but heading west of south. (In fact, throughout the whole

FIG. 241. The path of a plane *with reference to the air when flying a figure eight* with reference to the ground, with the wind blowing.



first half of the circle the plane is heading somewhat inward toward the pylon, and throughout the whole second half the plane is heading somewhat outward, away from the pylon.)

(6) To make the last quarter of the first circle and first quarter of the second circle, the pilot must execute two rather sharp curves with relatively steep banks. (At *A* the plane is momentarily level while shifting from a left bank to a right bank.)

(7) The second circle is executed in the same manner.

Flying the on-pylon eight

If a pilot flies around a pylon in such a way that his wing, or lateral axis, is always pointing directly toward the pylon he must fly, of course, at the *pivotal altitude* corresponding to his air speed, as explained in Chapter 18.

Also if the on-pylon eight is flown with a wind blowing, each loop of the eight must be a portion of an ellipse. This is because a complete on-pylon turn flown in a wind is an ellipse,[1] as shown in Figure 242. The pylon is at one focus of the ellipse. When the plane is flying exactly downwind opposite the pylon, it is at the end of the ellipse nearest the pylon (point *A*). When flying upwind it is at the other end of the ellipse (at *B*), and hence farthest from the pylon.

As you will see, the heading is always perpendicular to the line drawn from the pylon to the position of the plane, and the direction of the track at that point is shown by the tangent to the ellipse at that point.

The two wind-drift triangles illustrate the relation between the heading, the track, and the wind vector as the plane moves around the pylon.

[1] The fact that when wind is blowing an on-pylon turn is elliptical in shape is not widely understood by pilots, and has been more fully explained and proved, therefore, in an article by Arthur S. Otis entitled "Flying the On-Pylon Eight," published in the July, 1942, number of the *Aeronautical Engineering Review*.

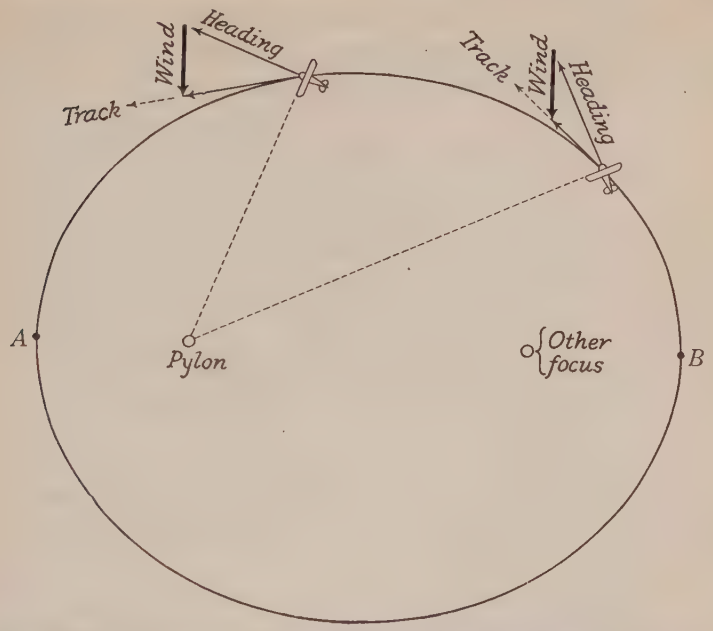


FIG. 242. The path of a plane flying an on-pylon turn in a wind.

As in flying a circle with reference to the ground, the plane is nearest level at the moment when flying upwind (farthest from the pylon in this case), and at that moment the ground speed is slowest.

The plane is banked most at the moment when flying downwind (nearest the pylon in this case) and at that moment the ground speed is fastest.

Figure 242 represents the path around the pylon when the wind speed is about two thirds of the air speed, as shown by the two wind-drift triangles. If the fraction is less, the path is more nearly a circle.

When flying a figure eight, whether circular or on-pylon, the pylons are so chosen that the line joining them is perpendicular to the direction of the wind. The pilot is required to fly between the pylons downwind.

In order to fly an on-pylon eight with the wind blowing it is necessary for the plane to fly a pattern with reference to the ground, as shown in Figure 243.

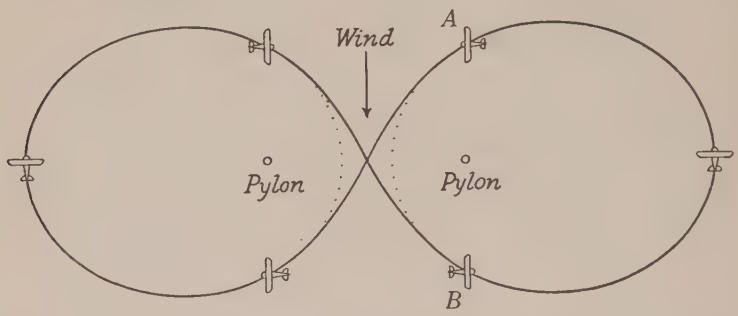


FIG. 243.

While passing from one ellipse to the other the plane must reverse its bank and for a few moments its wing cannot point to either pylon.

An important point to be noted is that in flying an on-pylon eight with wind blowing, the plane's distance from either pylon is continually changing. It is impossible in a wind to fly a loop around a pylon with the wing "on the pylon" at a constant distance from the pylon.

As in the circular eight, the plane is nearest level at the ends of the eight.

When the line joining the pylons is exactly at right angles to the direction of the wind, the figure eight is symmetrical with reference to the line joining the pylons, as shown in Figure 243. When flying directly crosswind at *A* (Fig. 243), the plane is just as far from the pylon as when flying crosswind at *B*; it has the same angle of bank and the same ground speed.

EXERCISE 2. Do you think you could find the trail of a plane which was flying a circle with reference to the ground in a wind blowing two thirds as fast as the air speed of the plane? If so, try it.

Questions

1. What is meant by flying a circular eight? an on-pylon eight?
2. What kind of figure eight is meant by the common expression "eight around pylons"?
3. What is meant by flying a circle with reference to the air? with reference to the ground?
4. Is the track of a plane flying a circle with reference to the air the same shape as the track of a plane flying a circle with reference to the ground?
5. What is the shape of the loop a pilot makes over the ground when flying an on-pylon eight?
6. How may a racer profit by understanding the nature of the relation between the track and the trail of a plane flying around a pylon?

27

DOWNDRAFTS

A SUBJECT seldom discussed in books and often disregarded by fliers is that of downdrafts. Yet in flying cross-country and in traversing mountains it is of vital importance that the pilot have a thorough understanding of downdrafts and their effect.

Nature and cause of downdrafts

When wind is blowing over a mountain the air must necessarily rise on the windward side of the mountain and sink on the leeward side, as shown in Figure 244.

The sinking air on the leeward side of the mountain is the *downdraft.*

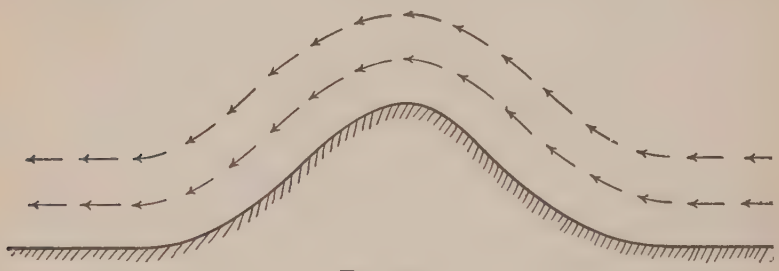


FIG. 244.

Similarity to wind drift

We have already seen in Chapter 23 how if a plane is headed east, as shown by the arrow AB in Figure 245, and the wind is blowing toward the southwest, as shown by the arrow BC, the actual motion of the plane will be in the direction AC.

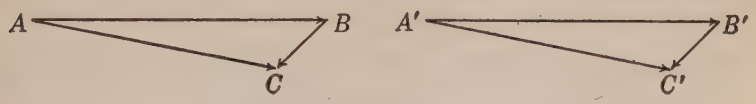


Fig. 245.

In exactly the same way, if a plane is flying in a level position — level with reference to the air — as shown by the arrow $A'B'$ in Figure 245 and the air is at the same time blowing downward in the direction of the arrow $B'C'$, the actual motion of the plane will be slightly downward in the direction $A'C'$.

Danger of a downdraft

What this means may be made clearer by an example. Let us say that a plane approaching a mountain in level flight encounters a downdraft and continues to fly level with reference to the air. It may fly directly into the mountain, as shown in Figure 246, even though approaching at a height above the top of the mountain.

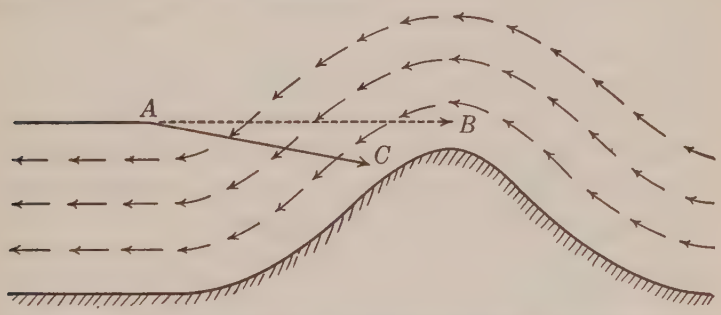


Fig. 246. The danger to an airplane of sinking in a downdraft.

As in Figure 245, while the plane would be flying from A to B if the air were stationary, the air has moved so that a balloon at B will have moved to C. Hence, if it continues to fly level with reference to the air, the plane is carried down to C.

How to fly over the mountain

For the plane to fly over the mountain it must *climb* from point A on; that is, it must climb with reference to the air, even in order to fly level over the mountain.

Thus, let us suppose a plane begins to climb at A in Figure 247, and climbs in the direction of AB. While the

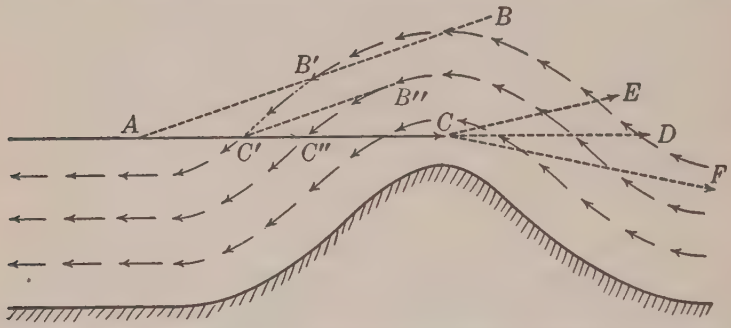


FIG. 247. The need for a plane to climb with reference to the air, in order to fly level in a downdraft.

plane is flying the distance AB' with reference to the air, the air itself moves so that point B moves to position C'. Consequently the plane actually flies from A to C'. Then as the plane flies from C' to B'' with reference to the air, point B'' will have been blown to position C'', and the plane will actually fly from C' to C''; and so on. That is, by climbing with reference to the air, the plane succeeds merely in flying level to C above the mountain.

The summit passed

After point C, just above the summit of the mountain, is reached no more climbing is necessary. In fact, while the plane merely flies level with reference to the air (as it would in flying from C to D in stationary air), point D will be blown to some point E; therefore the plane will actually rise to a higher altitude after passing the summit, even though flying in a level attitude.

The plane can actually glide down the rising air on the windward side and still retain the same altitude *CD*; that is, the plane can glide from *C* to *F* while *F* is rising to *D*.

The lesson

If you are approaching a mountain and the wind is blowing toward you, there will undoubtedly be a downdraft on the side of the mountain nearest you. And in that case, before you get near the mountain — before you encounter the downdraft — you should attain an altitude sufficient so that the downdraft will not carry you below the level of the summit.

But if you have not attained sufficient altitude and you find the plane beginning to sink in the downdraft, you must climb steeply enough with reference to the air to overcome the downdraft.

This second alternative is not always possible, as a downdraft may have more downward velocity than can be overcome by climbing. Remember that the greater the altitude the slower the plane can climb because of the lesser density of the air.

Strong downdrafts

It is well to realize that if the downdraft on the side of a mountain is more rapid than can be overcome by climbing, no amount of circling or zigzagging or flying back and forth parallel to the mountain *in the downdraft* will do any good. The mountain must be approached from a distance at an altitude such that the loss of altitude experienced while flying in the downdraft will not force the plane down to a level below the summit.

If the mountain has been approached at too low an altitude, there is nothing to do but fly back a sufficient distance from the mountain to avoid excessive downdraft, and there circle up to a safe altitude for approaching the mountain.

Gradual slopes

In some mountainous regions the approach to a summit or a pass is long and gradual. In such a situation, if the wind is blowing down the long slope the pilot may have a long, hard pull ahead, and he will need to get maximum altitude well in advance of his approach to the height he intends to pass.

Among the more difficult slopes to be encountered in transcontinental flying, one is on the approach to Albuquerque, New Mexico, from the east; and another is on the approach to Douglas, Arizona, from the northwest (along the airway). In these places the mesa rises to over 7000 feet.

However, even a present-day "flivver plane" of 50 horsepower, if in good condition, should be able to climb to 13,000 feet (possibly 14,000). Hence, if the climb is started early enough, there should be no difficulty in negotiating with such a plane any mountain pass of moderate elevation.

But, as we saw in Chapter 18, it takes considerable time to gain high altitude. For example, at normal cruising throttle, necessary to be used on a long climb, it might require a light plane 50 minutes to attain an altitude of 10,000 feet, and we must remember that in that length of time perhaps 60 miles of ground will have been covered. Hence it is well to start climbing early for a high altitude with possible downdraft.

Updrafts helpful

The pilot will naturally be more concerned over downdrafts than updrafts. However, it is well to realize that in traversing a mountain from the windward side much less altitude is necessary in the approach. Indeed, it is possible to approach a mountain at an altitude below that of the summit and to fly over the top without climbing, as shown in Figure 248.

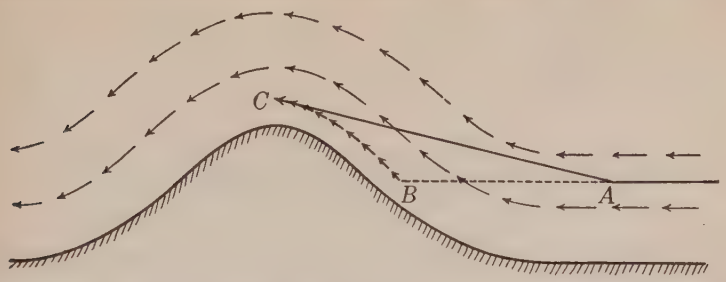


FIG. 248. The possibility of flying over a mountain from an altitude below the summit, without climbing, by making use of an updraft.

For example, while the plane would be flying level from *A* to *B* in Figure 248, in calm air, we may suppose point *B* of the air to be blown up to position *C*. Hence during that time the plane is actually lifted along the path *AC* and can fly over the top without climbing. Naturally, on the other side of the mountain the plane will sink to an altitude equal to that of point *A*, if it continues to fly level with reference to the air; but no danger is attached to this.

QUESTIONS

1. What causes a downdraft?
2. Can you explain the danger of a downdraft?
3. In what way is the effect of a downdraft similar to that of wind drift?
4. What is necessary to be done when encountering a downdraft?
5. Is a downdraft ordinarily accompanied by an updraft?
6. Is an updraft dangerous?
7. When is an updraft helpful?

28

AVIGATION BY RADIO RANGE

AS AN aid to avigation, the Civil Aeronautics Board maintains a number of stations, usually at or near airports, from which radio signals are broadcast. Each such radio signal station is called a *radio range station*.

The radio signals are broadcast at frequencies in a long-wave band called the *aviation band* (about 200 to 400 kilocycles). Each radio range station broadcasts its signals on its own wave length.

A pilot, having in his plane a radio which receives the aviation band, is able by tuning in to the wave length of a particular radio range station and getting onto the course of the "beam" (as explained below) to fly to or from the radio range station along the "beam."

Radio range beacons

By means of directional antennae a radio range beacon sends out signals which form a pattern, as shown in Figure 249.

The space around each station is divided by *beams* into four "quadrants." A *quadrant* is normally about a quarter of a circle, but the quadrants in this case may be considerably greater or less than a quarter of a circle, since the direction of a beam may be governed by the direction of an airway (see Chapter 43) or by the direction of some principal city from the radio range station.

In alternate quadrants the N signal (dash, dot) is broadcast and in the other two quadrants the A signal (dot, dash)

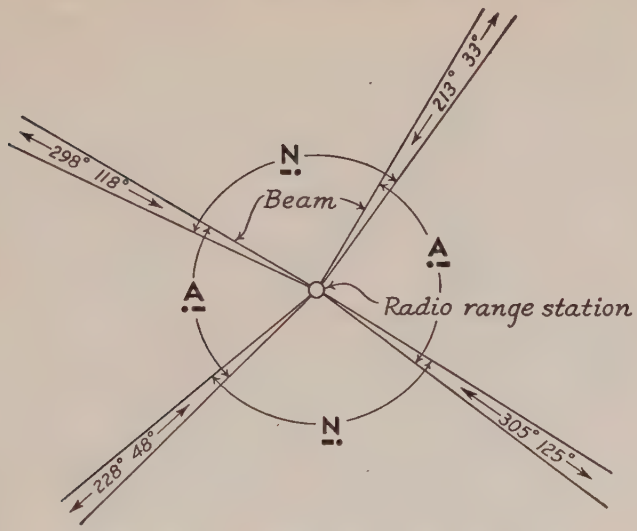


FIG. 249. A typical radio range pattern.

is broadcast. The N signal is always used in a quadrant that contains the direction northward from the station.

These signals are repeated about once each $2\frac{1}{2}$ seconds on a pitch about two octaves above middle C on the piano. The signals are interrupted each half minute by the station's identification letters (as WA for Washington), in order that the pilot may be sure of the station from which the signals are being received. (A partial list of identification letters is given on page 556.)

The N and A signals overlap between quadrants so that in the middle of the beam they form a continuous tone, as shown in Figure 250. On one side of the middle the N signal is slightly predominant, and on the other the A signal predominates.

FIG. 250. How the N and A signals merge to form the on-course signals.

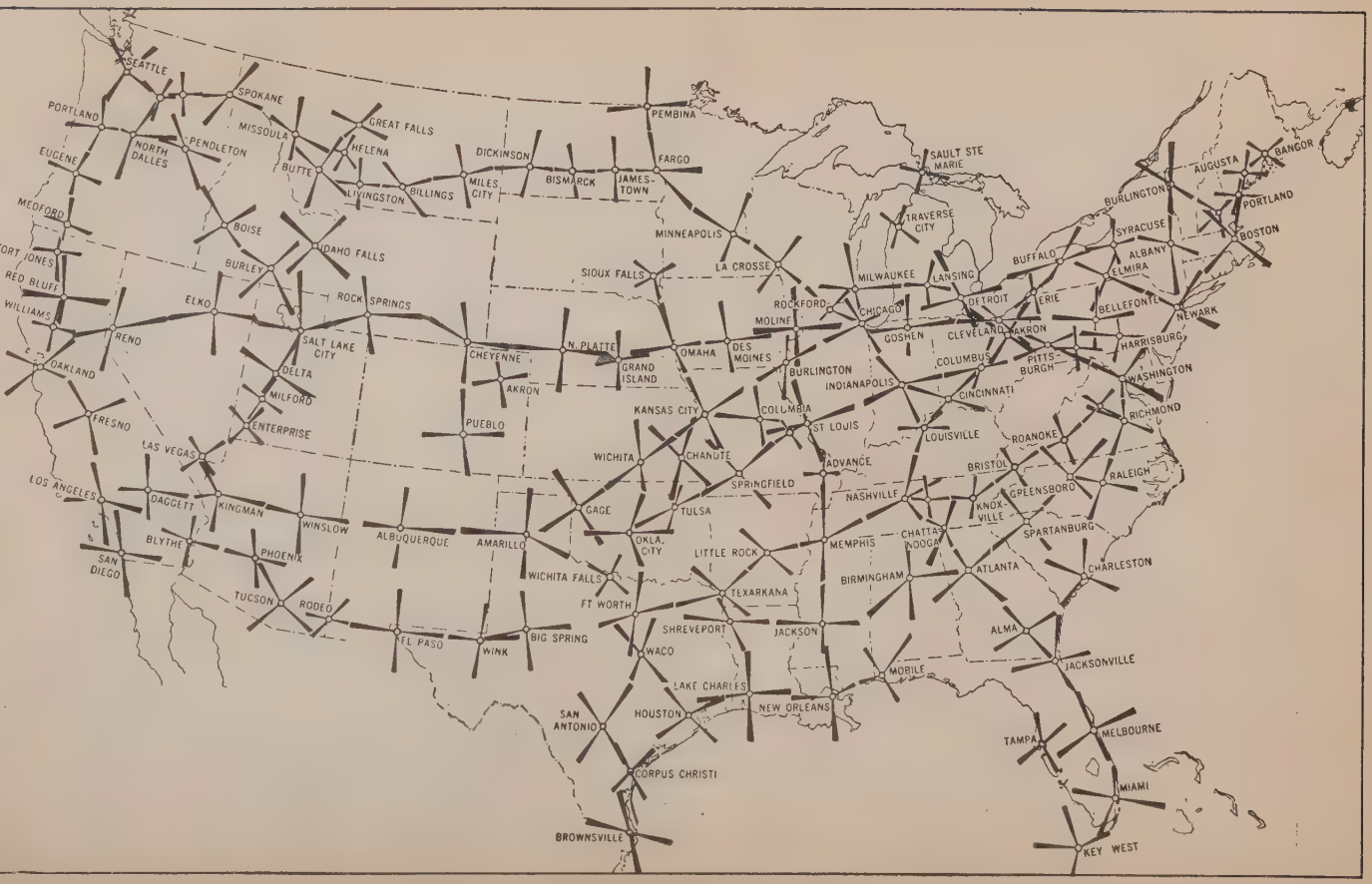


FIG. 251. The network of radio range stations.

Network of stations

The location of the various radio range stations is shown in Figure 251. It will be seen that in general the beams of adjacent stations point toward one another, so that a pilot may fly out on the beam of one station and in on the beam of the next station.

Directions of beams

Each radio range beam pattern is shown in pink on the aeronautical chart, and on each beam its direction toward and from the station is given, as shown in Figure 249. The chart also states the frequency number on which the beam is sent, and the station identification letters or signals.

Flying the beam

To fly a beam, the pilot tunes his radio to the station's frequency number, listens for the A or N signal and station identification, notes the direction in which the beam is proceeding from the station, and heads the plane in such a way as to merge his track with the beam, as shown in the upper quadrant of Figure 252.

To fly the middle of the beam the pilot tries to keep the *on-course* signal (continuous tone) in his earphones. When flying out a course with the N signal in the quadrant to the right, if he hears the N signal, he knows he is slightly to the right of the middle of the beam and so veers a little to the left; if he hears the A signal, he veers a little to the right. So long as he hears the on-course signal he continues straight ahead.

Keeping to the right

In flying a beam, a pilot, as a rule, keeps to the right of the middle. However, in flying to a station it is permissible

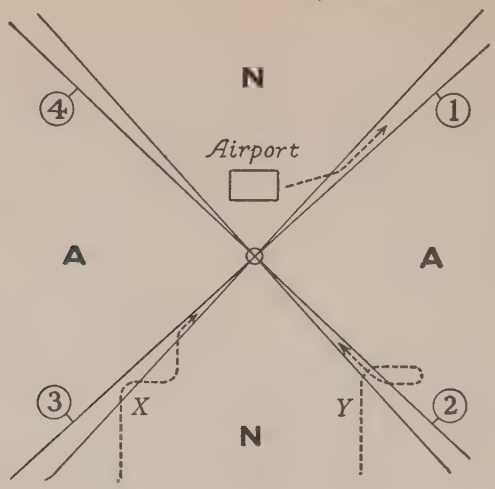


FIG. 252. Flying from and to a radio range station.

to fly the middle line of the beam. This is necessary as one nears the station, where the beam is narrow.

To fly on the right side of the beam, the pilot notes the signal that is on his right and flies so that that signal predominates slightly.

Cone of silence

Directly over the radio range transmitter there is a region in the shape of an inverted cone in which there is no signal. This is called the *cone of silence*. If a pilot is flying in on a beam the signals grow louder until the cone of silence is reached, when they suddenly cease. Then, after a few seconds the signals begin again, at first loud, then gradually diminishing.

Identifying a course

Suppose that a pilot is flying northward in the lower N quadrant of Figure 252. When he enters either course 2

or course 3, the N signal will fade into a continuous tone (on-course signal), and if he continues in a straight line the signal will grow into the A signal.

But, let us say, he does not know which course it is. A common method of identifying the course is as follows: The pilot turns sharply to the right or to the left and flies at right angles to his previous course. Let us say he chooses to turn to the right, as shown in Figure 252. If the signal changes back to N, the pilot knows he entered the left-hand beam, as shown at *X*. He then turns 90° to the left, continues till he hears the on-course signal again, then turns in the direction of the beam of course 3 (as shown by the chart) and follows the signal to the station.

If the signal changes to A and becomes stronger, the pilot knows he has crossed the right-hand beam, as shown at *Y*. He then makes a 180-degree turn to the right, and when he hears the on-course signal again he turns and flies in the direction of the beam of course 2 and follows it to the station.

By making this 180-degree turn to the right, the pilot makes sure that he will not encounter the on-course signal of course 1 or the cone of silence. If desired, as a matter of safety, the pilot may make a 180-degree turn to the right after identifying course 3.

Direction finders

A radio receiver with a loop antenna which can be rotated may be used as a *direction finder;* that is, as an instrument for finding the general direction of a radio range station, especially when one is not on a beam. When an N or A signal (or any broadcasting) can be heard, the loop is rotated until the signal fades to a minimum. The sending station is then in a direction at right angles to the plane of the loop. The pilot is presumed to know, from other sources, in which direction along this line the station lies.

Direction finder as a homing device

Assuming that the pilot knows which of the two directions is toward the station, he may so direct his flight that the signal remains at a minimum and thus bring his plane to the station. The direction finder is then said to be used as a *homing device.*

Radio compass

A direction finder as described above is sometimes called a *radio compass.* Strictly speaking, the term "radio compass" refers to the combination of a fixed antenna loop and a visual indicator. In one type, when the plane is headed directly toward the radio station, the indicator dial hand remains centered; when the plane is headed to the right or the left of the line to the station, the hand points to the right or the left accordingly. Another type has a needle on a 360-degree dial and shows the bearing of the station from the plane.

Allowing for the wind

Let us suppose that the broadcasting station is directly north of the position of the plane and that there is a strong east wind. The pilot will then not fly a track due north by heading the plane so that the signals are at a minimum with the loop crosswise of the plane. He will fly a curved track such as that shown in Figure 253. The curve is such that the angle between the curve (that is, the tangent to it) and the line directly toward the station, at any point P, equals the drift angle for the heading toward the station at that point.

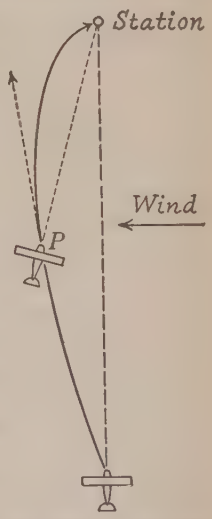


FIG. 253. The path of a plane following a radio compass without allowance for drift.

To fly a straight or approximately straight course, the pilot should apply the proper correction angle in the usual way, if he knows the wind velocity, and head the plane to windward of the desired course. A pilot, not knowing the wind velocity, can fly a straighter course by making an estimated allowance for wind than by making no allowance, as in Figure 253. If he applies just the right correction angle, the course will be straight. If the station still appears to move upwind as in Figure 253 (clockwise with the wind on the right), his correction angle is too small. If the station appears to move downwind, the correction angle is too great.

Establishing a fix

Finding one's location and orienting oneself is called establishing a *fix*. A pilot may know that he is flying toward a given radio station, but may not know how far he is from it. If by turning from one frequency to another the pilot can hear the signals from either of two stations, he may establish a fix as follows:

Let us say that he is at *A* in Figure 254 and can hear the signals from stations *B* and *C*. By means of his direction finder he obtains the bearings (direction) of stations *B* and *C* from his location. Suppose these to be 90° and 340°, as shown at the left in the figure.

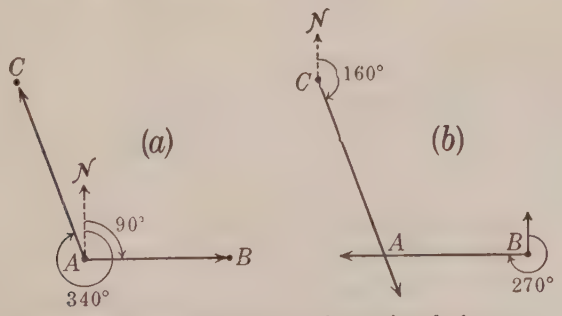


FIG. 254. Establishing a fix from signals from two radio range stations.

The pilot then finds the bearing of his location from each station by adding or subtracting 180°.

$$90 + 180 = 270°$$
$$340 - 180 = 160°$$

Hence he is in the direction 270° from B and in the direction 160° from A.

He then draws lines on the chart, one from B with a bearing of 270° and one from C with a bearing of 160°, as shown at the right in Figure 254, and the point of intersection is his position.

By measurement to scale he may then find out how far he is from his destination.

Allowing for an interval of time between observations

If both such observations of bearings are made within a short time, no correction need be applied; but the pilot may not hear signals from both stations at the same point. Nevertheless, he may establish an approximate fix from observations taken at different times in the following manner:

PROBLEM. In Figure 255 the bearing of B is taken at 12 : 00 o'clock and the bearing of C is taken at 12 : 15. The ground speed is known to be approximately 100 miles an hour; the plane is flying a track approximately north; the bearings are:

Bearing of B, 100°.

Bearing of C, 60°.

Let A be the position of the plane at 12 : 00 o'clock and A' the position of the plane at 12 : 15. These positions are to be found.

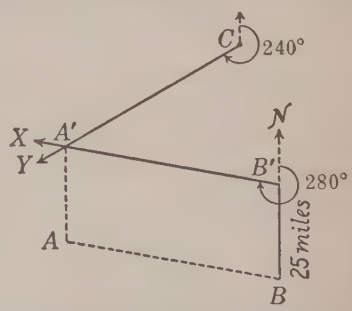


FIG. 255. Allowing for a lapse of time between two observations in establishing a fix.

The plane has flown the distance AA' in 15 minutes; hence AA' = about 25 miles. The bearing of A from B is $100° + 180°$, or $280°$. At 12 : 00 o'clock the plane is somewhere in the direction BA from B.

SOLUTION. 1. Find a point B' on the chart to which the plane would have flown from B in 15 minutes in the direction of flight. B' is 25 miles north of B in this case.

2. Draw a line $B'X$, having a bearing of 280°, hence parallel to line BA. Point A' lies somewhere on $B'X$. (The plane flying from any point on BA north for 25 miles is then on line $B'X$.)

3. Draw a line CY, having a bearing of $60° + 180°$, or 240°, from C. A' is somewhere on CY; hence where $B'X$ and CY intersect is A', the position of the plane at 12 : 15 o'clock.

Establishing a fix from one station

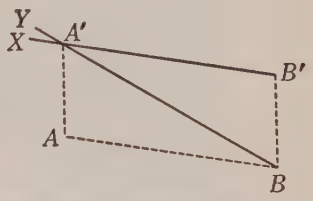


FIG. 255*a*. Establishing a fix from two observations of the same station.

The same method can be used if the second observation is made from station B instead of station C, as shown in Figure 255*a*. Here the steps are the same as before except that instead of drawing CY to represent the bearing of A' from C at 12 : 15, the line BY is drawn to represent the bearing of A' from B at 12 : 15.

Direction-finding charts

Actually, establishing a fix is not quite as simple as described above for the reason that the bearing of a radio station from a plane as determined by a direction finder is subject to the error of variation. That is, the bearing must be corrected for variation before it can be used as described above to find the true direction of the plane from the radio station.

For convenience in establishing fixes, *direction-finding charts* have been devised.

In such a chart (sometimes called a "D/F Map") there is a compass rose at each radio range station as shown in Figure 256 — except that the rose is printed in red. The station shown in the figure is Newark (NK).

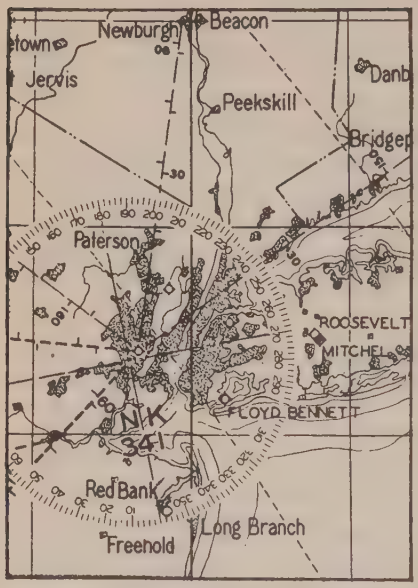


FIG. 256. A portion of a direction-finding chart.

Note that the rose is rotated 180° and then "cocked for variation." That is, 180° is set at magnetic north and 0° at magnetic south. This feature removes both the necessity to add or subtract 180° as described above and also the necessity to correct a direction-finder reading for variation.

Thus if the magnetic bearing of NK from a plane is 300°, the pilot has only to draw a line from station NK through 300° on the rose to find the true direction of the plane from the station as of the time of making the observation.

Morse code

The code of signals by which letters and numbers are indicated by the "dots and dashes" of radio signals is called the *Morse code*. It is well to know or be able readily to refer to the Morse code, to identify the radio range stations from which signals are heard. The Morse code is as shown in Table 13. It is given twice, once in alphabetical order and again (columns 3 and 4) in an order for convenient reference in finding the letter from the signal.

EXERCISE 1. Assume that there is a radio range station at Fort and another at Eden (Exercise Chart). A pilot hears the Fort signal from 135°; and 5 minutes later, flying northward with a ground speed of 90 miles an hour, he hears the Eden signal from 45°. How far is he from Eden when he hears the Eden signal?

EXERCISE 2. A pilot flying west at a ground speed of 90 miles an hour hears the Fort signal from 190°. Ten minutes later he hears the Fort signal from 170°. How far from Fort is he then?

TABLE 13

THE MORSE CODE

A · —	N — ·	E ·	T —
B — · · ·	O — — —	A · —	N — ·
C — · — ·	P · — — ·	R · — ·	K — · —
D — · ·	Q — — · —	L · — · ·	C — · — ·
E ·	R · — ·	W · — —	D — · ·
F · · — ·	S · · ·	P · — — ·	B — · · ·
G — — ·	T —	J · — — —	X — · · —
H · · · ·	U · · —	I · ·	Y — · — —
I · ·	V · · · —	U · · —	M — —
J · — — —	W · — —	F · · — ·	G — — ·
K — · —	X — · · —	S · · ·	Z — — · ·
L · — · ·	Y — · — —	V · · · —	Q — — · —
M — —	Z — — · ·	H · · · ·	O — — —

QUESTIONS

1. What is a radio range station?
2. What is a "quadrant" when we are speaking of radio ranges?
3. Why were the letters A and N chosen for radio range signals?
4. What is the on-course signal and how is it formed?
5. Airport *X* is exactly north of a radio range station. In what quadrant is it, the A or the N?
6. How does a pilot keep on the course of a beam?
7. What is a cone of silence?

8. If a pilot first finds himself in an A quadrant with the signals getting stronger and later gets an on-course signal, how can he identify it so that he can follow it?
9. What is a direction finder?
10. What is a homing device?
11. When a plane is heading toward a radio station in a wind, guided by a direction finder, what kind of track does it make?
12. How may a pilot establish a fix by means of a direction finder?
13. What is the Morse code? How many letter signals do you know?
14. What is a radio compass?
15. What station is represented by these signals? — · — · —
16. The signals · — · · — — · denote what letters?
17. What is the signal for Washington (W A)?

PART IV

METEOROLOGY

Transcontinental and Western Air, Inc.

FIG. 257. A passenger plane flying above the clouds.

29

WEATHER HAZARDS IN FLYING

EVEN a motorist has to meet some weather hazards. He has to understand the danger of skidding on icy or snowy pavements, the danger of wheels sinking into deep snow with loss of traction, the danger of the freezing of water in the radiator, the danger of rain causing short circuits, etc.

Since a pilot is traversing the air in which the weather originates, it is all the more necessary that he know how to avoid the hazards of weather.

Hazards to flying

Among the weather hazards to flying are clouds and fog that obscure vision of the ground and horizon; strong winds that make take-offs and, especially, landings dangerous; icing of the wings, with consequent loss of lift; strong head winds that impede progress; wind drift and shifting of winds that affect navigation and sometimes throw a pilot off his course; downdrafts that impede flying over mountains; snowstorms; and thunderstorms with extreme turbulence and lightning.

Let us consider the danger of flying in a cloud or fog.

The danger of flying in clouds

It is dangerous to fly in a cloud other than a small one from which you can promptly emerge. The principal reason is that you need to be able to see the ground and to know where the horizon is in order to keep the plane level.

If you are flying in a cloud the plane may veer off in a curve, tip more and more, and eventually go into a dive; and you may not realize what is happening without seeing the horizon, for as you sit in the plane the feeling can be the same in such a case as if you were flying straight and level.

Of course, if you have begun to dive, you will realize that the plane is gaining speed through the air and you will assume that it is diving; but even though you attempt to pull it up to level you will have no idea, without glimpsing the horizon, where "level" is and you may pull the plane up to a stall, or if it is banked you may merely pull it into a tighter curve.

In short, if you do not have special instruments you cannot fly safely in a cloud or a fog.

There are instruments that may be used in a plane to enable the pilot to fly straight and level without seeing the ground or horizon, and to know to what extent he is climbing or turning. These are described in Chapter 39 on Instrument Flying. However, the ordinary plane is not equipped with such instruments for "instrument flying" and the use of them requires special advanced training. This means that the ordinary pilot must keep clear of clouds.

It is true that a pilot who is flying above a solid bank of clouds can see the horizon, or at least he can tell from the top surface of the clouds whether or not his plane is level and going straight; and so long as he can stay above the clouds he can fly safely. But the time arrives when the pilot must come down, and if this requires flying through a solid layer of clouds (an overcast), the danger is then just as great no matter how long the pilot may have flown "over the top."

This means that if a pilot is flying above a bank of scattered clouds and finds the clouds becoming more and more solid, he must fly down through some open space among the clouds before they close together under him.

The danger of fog

Even if the clouds close in under the plane and form an overcast, it is possible that the pilot may be able to get down through the clouds safely. That is, even if the plane is diving and the pilot is not able to control it, he may still have time, after coming out below the cloud bank, to right the plane and make a safe landing, if there is enough open space between the clouds and the earth.

However, clouds sometimes come right down to the earth, leaving no space between the clouds and the earth. In that case we call the cloud a fog.

Obviously, if a pilot tries to come down through a cloud that is resting on the ground, so to speak, he is almost sure to crash, because he will not be able to pick out a landing place or be able to see the ground soon enough to level off.

Flying in a fog therefore is very dangerous! — without the special instruments for instrument flying.

It is clearly of the greatest importance for a pilot to know the state of the weather ahead, especially at the airport where he intends to land. If there is any question about the weather at the destination, the pilot should select and keep in mind an alternate airport to which he may fly if necessary. This airport should be one where there is assurance of the continuance of suitable flying weather, and it must be within the fuel range of the plane.

The cautious pilot will habitually select an alternate airport on all long flights, even when flying under ordinary conditions. It is important, therefore, that the pilot know the weather conditions over the entire area within the fuel range of his plane.

Meteorology

The science of the weather is called *meteorology*. There is a meteorologist stationed at each of the principal airports

of the United States, whose business it is to observe weather conditions at regular intervals at that airport, to report the observations to other airports, to receive observations from other airports, and to make these available to fliers.

The weather service maintained by the Weather Bureau of the United States Department of Agriculture is necessarily highly complicated and therefore highly systematized. The observation stations are spread out to cover entirely the United States and its possessions. Reports are received by radio of observations made on vessels at sea. Observations are exchanged with the meteorological services of foreign governments. Not only is the entire United States covered; at Washington, D. C., weather maps are regularly drawn covering the entire world. To collect and then distribute the substance of these many observations requires a gigantic system of communications which employs telephone, telegraph, teletype, and radio.

The service includes (1) the making of observations, (2) the analysis and synopsis of the observations, and (3) the making of forecasts.

Observations are to be considered as reasonably accurate, and they may serve as the basis for a pilot's own judgment about safety for flying. The analysis and synopsis of the observations and particularly the forecasts are subject to additional errors.

Analysis and synopsis of observations

We may think of analysis and synopsis as the taking apart and putting together of weather observations. From the study of actual observations of temperature, pressure, and other phenomena reported from various weather stations, a meteorologist may determine by inference the points on the earth's surface where similar conditions exist, and draw lines on a map joining such points. Lines that join points of equal temperature are called *isotherms;* those that join

points of equal pressure are called *isobars*. Other lines may be drawn to denote equality in other measurements. The drawing of such lines on his base maps gives the meteorologist a general view of the state of the weather over a large area. Obtaining a general view of weather over a large area is called *synopsis*. These weather maps, or synoptic charts, are made available to pilots; and a pilot who is versed in the science of meteorology is able to obtain a great deal of information from them.

Forecasts

The Weather Bureau designates some of its meteorologists to make forecasts for airways — judgments about what the weather will be during a given period. These judgments are based on the latest synoptic charts, studied in the light of preceding charts, and on the forecaster's long experience in observing how weather behaves in relation to the nature of the various synoptic charts and other available information. The forecasts are made every six hours for the next succeeding eight hours. They are official statements and must be transmitted and quoted precisely as made. They become a matter of permanent record and may even be used in court.

Forecasts must not be regarded as infallible, and no pilot relies on them implicitly. He must always supplement forecasts with his own observation and judgment. The better meteorologist he is himself the better he can evaluate forecasts and supplement them in the light of his own observations, and the better he can interpret forecasts as they may apply to his own proposed flight.

Inquiring about the weather

Any pilot can and should determine before beginning any extended trip from an airport just what the weather is at

his destination — or was at the last report — and at any alternate airport he may select; also what the forecasts may be.

The meteorologist does not advise the pilot that it is or is not advisable to make the proposed trip. It would not be possible for him to do so correctly even if he were so inclined, because the safety of making a trip depends so largely on the pilot's plane and equipment and upon his knowledge and skill.

The meteorologist shows the pilot the reports of the weather observations and the official forecasts, and the pilot must make up his own mind as to the wisdom of making the proposed trip.

There are occasions when a pilot wishes to take off from a point where no weather reports or forecasts are available. For example, a pilot may have made a forced landing in a pasture and the weather may have changed by the time he was ready to take off. In such a case he would have to rely on his own interpretation of the weather from such observations as he himself could make.

Since it is so important for every pilot to have a basic knowledge of weather and its relation to flying, it seems desirable to begin with the fundamentals. In the next chapter, therefore, we consider the earth and its atmosphere.

Questions

1. What hazards to flying can you name?
2. Explain the dangers of flying in a cloud.
3. How does a fog differ from a cloud?
4. Is the danger of flying in a fog greater or less than the danger of flying in a cloud?
5. What does the term *meteorology* mean?
6. What is a meteorologist?
7. Under what circumstances may a pilot be required to depend upon his own knowledge of meteorology?

30

THE EARTH AND ITS ATMOSPHERE

IT HAS been said that we live at the bottom of an ocean of air. The air does not have a definite upper surface like an ocean of water but becomes thinner and thinner with higher altitudes until it fades away imperceptibly into space. Faint traces of air are believed to exist as high as 600 miles above sea level; but about half of all the air lies below a height of 18,000 feet.

The weight of air

Air is not nearly so heavy as water, and yet the weight of the whole ocean of air around the earth is about six million billion tons. The air in a room 10 feet square and 10 feet high weighs about 77 pounds. A column of air one square inch in cross-section extending up to the top of the atmosphere weighs 14.7 pounds; hence the air presses on everything it touches with a pressure of 14.7 pounds to the square inch.

Upper air is cold

The air becomes colder as we go higher in it, up to a height of about 36,000 feet in the temperate zones. At this altitude the air is down to 67° F. below zero (− 67° F.). Above 36,000 feet (or a little over 7 miles up) the air has about the same temperature no matter how great the altitude.

Troposphere and stratosphere

The layer of air below about 36,000 feet, within which the temperature becomes colder as you go up, is called the

troposphere. The upper air above 36,000 feet, which has an approximately constant temperature, is called the *stratosphere*. The boundary between the troposphere and the stratosphere is called the *tropopause*.

The troposphere extends to only about 7 miles at the poles and to about 11 miles at the equator. All clouds, turbulence, and precipitation occur in the troposphere. The stratosphere may contain high winds, but it is clear and the winds are steady. (See Fig. 258.)

Composition of the air

The air is a physical mixture of a number of gases. The most abundant is nitrogen, constituting 78 per cent of dry air; the next is oxygen, 21 per cent, which is essential to life. All the others together, of which argon and carbon dioxide form the bulk, constitute the remaining 1 per cent.

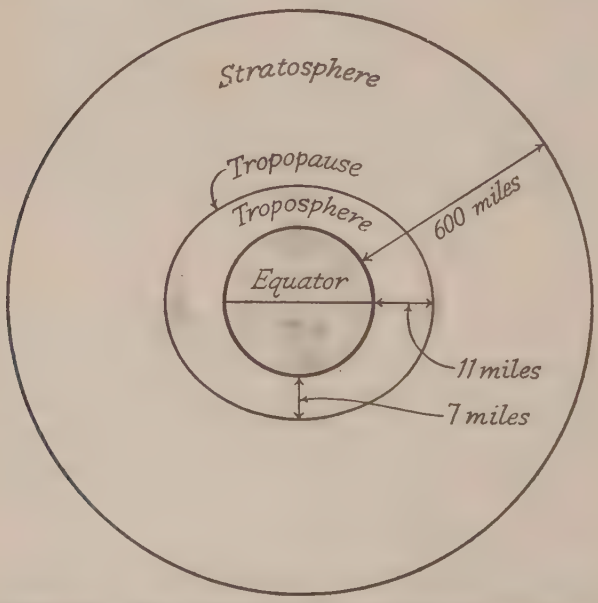


FIG. 258. The earth and the layers of the atmosphere

The gases are mixed in the same proportions at all altitudes.

In addition to the gases constituting dry air, there is present everywhere in the troposphere more or less water vapor.

It is the water vapor, now condensing as clouds, rain, snow, or hail, and again evaporating, that gives fliers so much to be concerned about.

In middle latitudes the average proportion of water vapor present in air at the surface is about 1.2 per cent by volume. Water vapor weighs about $\frac{5}{8}$ as much as dry air (per molecule).

The cause of weather

The phenomena that we generally think of as weather — clouds, rain, wind — depend upon changes in a number of characteristics of the atmosphere, the principal of these characteristics being temperature, heat content, pressure, and humidity. We must now investigate the interaction of changes in each of these upon the others. This involves a careful study of what are known as *adiabatic lapse rates.* These are discussed in the next chapter.

Questions

1. How do we find the air differing as we go higher in it?
2. How high does the atmosphere extend?
3. One half the air lies below what altitude?
4. What does the air in a room 10 feet square and 10 feet high weigh?
5. What is the normal pressure of air on a square inch of surface?
6. Why does the air not crush our bodies?
7. How does the temperature of the air change as we go up in it?
8. What is the stratosphere?
9. What is the troposphere?
10. What is the tropopause?

11. How high up is the tropopause?
12. What element is most common in the air? next most common?
13. What per cent of air is nitrogen? oxygen?
14. Water vapor constitutes about what per cent of the volume of air, on the average?
15. How does the weight of water vapor compare with that of air?
16. What do clouds consist of?

31

ADIABATIC LAPSE RATES

IF WE had a pile of books, each weighing a pound, the force on the next to the top book would be one pound, the force on the next book would be two pounds, and so on down. Similarly, the pressure of the air at any height is the result of the weight of the air above that height, and as we ascend in the atmosphere we find the air exerting less and less pressure.

The barometer

Air pressure is measured by a *barometer*. The simple mercury barometer is a closed tube filled with mercury, inverted, and placed upright with its open end in a pan of mercury (Fig. 259). The mercury sinks in the tube to a height such that the weight of the mercury in the tube can just be held up by the pressure of air on the mercury in the pan. The space above the mercury is a vacuum. At sea level the height of the mercury in a barometer tends to be about 29.9 inches.

FIG. 259. A simple mercury barometer.

Pressure is commonly measured in terms of "inches of mercury" — meaning the height of mercury in the barometer in inches. Figure 259 indicates "a pressure of 30 inches."

As we go up in the atmosphere and the pressure becomes less, the mercury sinks in the tube and its height in inches diminishes. "The barometer falls," we say.

Table 14 shows how the pressure of the air tends to decrease with altitude. The values indicated are only average figures and do not necessarily apply to air in any specific case.

TABLE 14

SHOWING THE AVERAGE CORRESPONDENCE BETWEEN BAROMETRIC PRESSURE (IN INCHES) AND ALTITUDE IN FEET ABOVE SEA LEVEL; ALSO BETWEEN MILLIBARS AND ALTITUDE IN FEET

ALTITUDE IN FEET ABOVE SEA LEVEL	PRESSURE IN INCHES OF MERCURY	PRESSURE IN MILLIBARS
18,000	14.92	505
16,000	16.20	548
14,000	17.57	594
12,000	19.03	644
10,000	20.58	696
8,000	22.22	752
6,000	23.98	811
4,000	25.84	875
2,000	27.82	941
0	29.92	1013

Millibars

Another measure of pressure used by meteorologists is based on a unit called a *millibar*. A millibar is a force of 1000 dynes per square centimeter. A *dyne* is a metric unit of force. The pressure of 1 inch of mercury equals about 34 millibars (33.86395).

Table 14 shows also the decrease in millibars of pressure with increase in altitude.

If we examine Table 14 we see that near sea level the decrease in barometric pressure is about 1 inch of mercury for each 1000 feet, whereas at between 16,000 and 18,000 feet the decrease is only about .7 inch of mercury for each 1000 feet. The pressure has decreased by a quarter at about 8000 feet up from sea level; by another quarter in about

the next 10,000 feet; a third quarter in about the next 18,000 feet. And then you have to go all the way to the top of the stratosphere, say 3,000,000 feet, to lose the last quarter of the pressure.

Boyle's law

An Irish scientist, Robert Boyle, discovered about 1650 that *the volume of a given quantity of gas at constant temperature is inversely proportional to the pressure.* This is known as *Boyle's law*, and sometimes as *Mariotte's law*, after Edme Mariotte, a Frenchman who independently discovered the same principle at about the same time.

It means that if a given quantity of gas is kept at constant temperature, the following will be true:

(1) Doubling the pressure (as by a piston in a cylinder) reduces the volume to one half.

(2) Reducing the pressure to one half allows the gas to expand to double the volume. A gas is indefinitely expansible and tends to occupy all the space available.

(3) Doubling the volume (allowing the gas twice as much space) reduces the pressure to one half.

(4) Reducing the volume to one half makes the pressure twice as great.

Boyle's law can be expressed as a formula as follows:

$$\frac{P_n}{P_o} = \frac{V_o}{V_n} \quad \text{or} \quad P_n = \frac{V_o}{V_n} P_o \qquad \text{(Formula of Boyle's law)}$$

in which —

P_o = "old" or (original) pressure
P_n = "new" pressure
V_o = old volume, and
V_n = new volume

In order to understand the composition of the atmosphere you need to know two other laws pertaining to gases; and it will be a great convenience, in connection with these laws,

to have a familiarity with the Centigrade temperature scale. We must digress briefly, therefore, and consider the relation of the Centigrade thermometer to the Fahrenheit thermometer. The Fahrenheit thermometer is the kind commonly used in the home. The Centigrade thermometer is used most frequently in scientific measurement of temperature.

Fahrenheit and Centigrade thermometers

On the common Fahrenheit mercury thermometer the freezing temperature of water is 32°, and the boiling point is 212°. On the Centigrade thermometer, with a different scale, the freezing temperature of water is 0° and the boiling point is 100°. The two thermometer scales are shown in Figure 260.

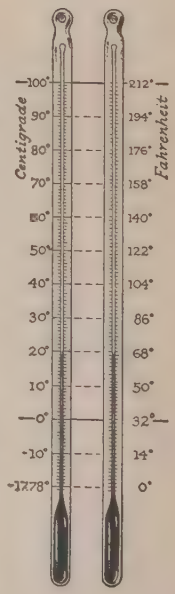


FIG. 260. Centigrade and Fahrenheit thermometers.

Relation of the Centigrade scale to the Fahrenheit scale

It takes 9 units on the Fahrenheit scale to equal 5 units on the Centigrade scale; and since 0° C. = 32° F., the relation between the scales is expressed by the following formula:

$$F = \tfrac{9}{5}C + 32$$
$$\text{or} \quad C = \tfrac{5}{9}(F - 32)$$

(Formulas for changing Centigrade to Fahrenheit and vice versa)

Problems 1 and 2 illustrate the changing of Centigrade readings to Fahrenheit, and vice versa.

PROBLEM 1. Change 25° C. to Fahrenheit.

SOLUTION. Solve the formula $F = \frac{9}{5}C + 32$.

1. $F = (\frac{9}{5} \times 25) + 32$
2. $F = 45 + 32 = 77°$

Hence $25°\ C = 77°\ F$

PROBLEM 2. Change 26° F. to Centigrade.

SOLUTION. Solve the formula $C = \frac{5}{9}(F - 32)$.

1. $C = \frac{5}{9}(26 - 32)$
2. $C = \frac{5}{9}$ of $-6 = -(\frac{5}{9}$ of $6) = -3\frac{1}{3}$

Hence $36° F = -3\frac{1}{3}° C$

EXERCISE 1. Change the following temperatures to Fahrenheit: (*a*) 10° C., (*b*) 28° C., (*c*) 36° C.

EXERCISE 2. Change the following temperatures to Centigrade: (*a*) 50° F., (*b*) 56° F., (*c*) 22° F.

Charles's discovery

A French chemist, Jacques Alexandre Charles (pronounced *shärl*), discovered in 1787 that if the volume of a given quantity of gas is held constant, the pressure of the gas decreases with decrease in temperature. Beginning at 0° C., the pressure of the gas decreases $\frac{1}{273}$ of the 0° C. pressure with each decrease of 1 degree. It is as if the pressure of a gas would be reduced to zero if the temperature were reduced to − 273° C.

Gay-Lussac's discovery

Joseph Louis Gay-Lussac, a French chemist, discovered in 1802 that if a gas is held at the same pressure, the volume of the gas is reduced $\frac{1}{273}$ of the volume of 0° C. for each degree that the temperature may be reduced below 0° C. It is as if the gas at constant pressure would have no volume at all if it could be reduced to − 273° C.

Absolute temperature

From the discoveries of Charles and Gay-Lussac it is believed that − 273° C. is the lowest possible temperature. Hence − 273° C. has been called 0° Absolute temperature (0° A.).

This means that

$$-273^\circ C = 0^\circ A$$
$$-272^\circ C = 1^\circ A$$
$$-271^\circ C = 2^\circ A$$
$$-270^\circ C = 3^\circ A$$
$$-269^\circ C = 4^\circ A, \text{ and so on.}$$

The relation of Absolute and Centigrade readings may be expressed in formulas, thus:

$A = C + 273$ (Formulas for changing Centigrade
$C = A - 273$ to Absolute and vice versa)

Charles's law

Charles's discovery is stated as a law as follows: *If a given quantity of gas is held at constant volume, the pressure is directly proportional to the Absolute temperature.* This is called *Charles's law.*

This means that if a given quantity of gas is held at constant volume, the following will be true:

(1) Doubling the temperature (by adding heat) doubles the pressure.

(2) Reducing the temperature to one half (by cooling) reduces the pressure to one half.

(3) In order to double the pressure, the Absolute temperature must be doubled.

The doubling is accomplished by heating, for we cannot hold the volume constant and forcibly double the pressure and thus get a higher temperature.

(4) In order to reduce the pressure to one half we must reduce the temperature to one half the Absolute temperature by cooling.

Charles's law can be expressed in a formula as follows:

$$\frac{P_n}{P_o} = \frac{T_n}{T_o} \quad \text{or} \quad P_n = \frac{T_n}{T_o} P_o \quad \text{(Formula for Charles's law)}$$

Gay-Lussac's law

Gay-Lussac's discovery is also stated as a law, known as *Gay-Lussac's law*, as follows: *If a given quantity of gas is held at constant pressure, the volume is directly proportional to the Absolute temperature.*

This means that if a given quantity of gas is held at constant pressure, as if held in an upright cylinder by a piston of given weight, the following will be true:

(1) Doubling the Absolute temperature (by adding heat) doubles the volume.

(2) Reducing the Absolute temperature to one half (by cooling) reduces the volume to one half.

(3) In order to double the volume the Absolute temperature must be doubled (by heating).

(4) In order to reduce the volume to one half, the Absolute temperature must be reduced to one half. (We cannot hold the pressure constant and forcibly change the volume. The volume can be changed in that case only by heating or cooling.)

Gay-Lussac's law can be expressed in a formula as follows:

$$\frac{V_n}{V_o} = \frac{T_n}{T_o} \quad \text{or} \quad V_n = \frac{T_n}{T_o} V_o \quad \text{(Formula for Gay-Lussac's law)}$$

Three laws combined

We may combine Boyle's, Charles's, and Gay-Lussac's laws into one law which is expressed in the following formula:

$$\frac{P_n V_n}{P_o V_o} = \frac{T_n}{T_o} \quad \text{(Formula for relation of pressure, volume, and Absolute temperature of a gas)}$$ [1]

[1] This formula holds good regardless of the units of pressure and volume used, so long as *zero* for these means *not any*. But the temperature must also be measured in units of which 0° means *not any temperature;* hence we cannot use Fahrenheit or Centigrade. We must use a temperature scale in which 0° = − 273° C.

In this combined formula —

P_o, V_o, and T_o are the pressure, volume, and Absolute temperature of a given amount of gas under one condition and P_n, V_n, and T_n are the pressure, volume, and temperature of the same amount of gas under any new condition.

If $T_n = T_o$, the formula states Boyle's law;
if $V_n = V_o$, the formula states Charles's law;
if $P_n = P_o$, the formula states Gay-Lussac's law.

The use of the combining formula is illustrated in the problem that follows.

PROBLEM 3. If a quantity of gas at a pressure of 30 inches of mercury has a volume of 3 cubic feet at $-3°$ C., what will the pressure be when the volume is 5 cubic feet and the temperature is 87° C.?

SOLUTION. Solve the formula $\frac{P_n V_n}{P_o V_o} = \frac{T_n}{T_o}$.

1. $T_n = 273° + 87° = 360° A$
2. $T_o = 273° - 3° = 270° A$
3. $P_n = x \qquad P_o = 30$
4. $V_n = 5 \qquad V_o = 3$

Substituting these values in the formula —

5. $\frac{x \times 5}{30 \times 3} = \frac{360}{270}$ But $\frac{360}{270} = \frac{4}{3}$, hence
6. $\frac{5x}{90} = \frac{4}{3}$
7. $5x = \frac{360}{3} = 120$
8. $x = 24$ The pressure will be 24 inches of mercury.

EXERCISE 3. What would be the pressure of the gas in Problem 3 if the volume were 4 cubic feet and the temperature 450° A.?

EXERCISE 4. What would be the volume of the gas in Problem 3 if the pressure were 20 inches of mercury and the temperature 177° C.?

EXERCISE 5. What would be the temperature of the gas in Problem 3 if the pressure were 15 inches of mercury and the volume 2 cubic feet?

Now we are ready to give more consideration to the behavior of a body of air being raised or lowered in the atmosphere, and to understand how air comes to be thus raised or lowered.

Air expands as it is lifted in the atmosphere

As we said, air is indefinitely expansible and always occupies the largest space available. Hence any body of air, whether in a balloon or in a soap bubble or free, expands as it moves from a region of high pressure to a region of low pressure; and in the atmosphere, where pressure decreases as we move upward, we find that air expands as it is moved upward.

At the San Francisco Exposition of 1940 there was a particularly interesting petroleum exhibit. In several huge glass tubes of oil, bubbles of air were slowly rising, one after another. Each bubble might be 2 inches in diameter at the bottom of the tube, and as it rose it would gradually expand to perhaps 3 inches in diameter at the top of the tube. Air expands when it rises in the atmosphere, just as a bubble expands when it rises in water or oil.

Contrariwise, a body of air that is sinking in the atmosphere is compressed (it contracts) more and more as it sinks.

Rising (expanding) air becomes less dense

Obviously, if the same mass of air which occupied 1 cubic foot at sea level expands to occupy 2 cubic feet at some altitude above sea level, it must be less dense at that altitude.

Conversely, sinking (contracting) air becomes more dense.

Rising air cools as it expands

When air rises or is forced up in the atmosphere, the pressure on it is reduced. If a body of air is lifted to 18,000 feet altitude, the pressure is only one half what it was at sea level.

If the temperature of air remained constant while it was lifted to 18,000 feet, the volume would double, according to Boyle's law.

If the volume remained constant, the temperature would fall to one half the Absolute temperature, according to Charles's law.

But neither of these things happens. What does happen is that the volume increases until it is somewhat less than double and the temperature decreases by somewhat less than one half. That is, the volume of 1 cubic foot of air at sea level increases in the above case to about 1.75 cubic feet, and the temperature actually decreases only to about .87 of the Absolute temperature it had at sea level.[1]

The decrease in temperature is about 5.5° F. for each 1000 feet of elevation.

[1] According to the combined formulas,

$$\frac{P_n V_n}{P_o V_o} = \frac{T_n}{T_o} \quad \text{or} \quad \frac{P_n}{P_o} \times \frac{V_n}{V_o} = \frac{T_n}{T_o}$$

In the above case of the lifting of 1 cubic foot of air to the altitude (18,000 feet) at which its pressure is $\frac{1}{2}$ the sea level pressure,

$$\frac{P_n}{P_o} = \frac{1}{2} \quad \text{and} \quad \frac{V_n}{V_o} = 1.75.$$

Substituting these values in our formula, we get

$$\frac{T_n}{T_o} = \frac{1}{2} \times 1.75 = .875$$

The value 1.75 of $\frac{V_n}{V_o}$ is found by noting that at 18,000 feet where the pressure is $\frac{1}{2}$ the sea-level pressure the number of slugs per cubic foot is .001359, whereas the number of slugs per cubic foot at sea level is .002378. The volume of a slug at 18,000 feet is therefore $\frac{.002378}{.001359}$ as great as the volume of a slug at sea level. This fraction = 1.75.

Sinking air warms as it is compressed

When air sinks (subsides) or is forced down in the atmosphere, it passes from a region of one pressure to a region of higher pressure; hence it is compressed and also warmed. It is warmed about 5.5° F. for each 1000 feet of *subsidence*. One cubic foot of air taken at 18,000 feet, when brought down to sea level where the pressure is double, has its volume reduced by an amount somewhat less than half, and has its temperature increased but not doubled.[1]

Temperature lapse rate

When the temperature decreases with changes in pressure and volume, we can say that the temperature *lapses*. One definition of the word "lapse" is this — a gradual falling from a higher to a lower state or amount. Hence the rate at which temperature decreases with the changes in pressure and volume is called a *temperature lapse rate*, or merely a *lapse rate*.

Adiabatic process

Any change in pressure, temperature, volume, and density which occurs in air or in any gas without the addition or subtraction of heat is called an *adiabatic* (ăd-ĭ-*ȧ*-băt'ĭc) *process*.

In this chapter we are concerned with only those adiabatic changes that occur in dry air. In a later chapter those occurring in moist air will be discussed.

Adiabatic lapse rate

The temperature lapse rate in an adiabatic process is called an *adiabatic lapse rate*.

[1] In this case $\frac{P_n}{P_o} = 2$, and $\frac{V_n}{V_o} = .57$ (.001359 = .57 of .002378)

Hence $$\frac{T_n}{T_o} = \frac{P_n}{P_o} \times \frac{V_n}{V_o} = 2 \times .57 = 1.14$$

The adiabatic lapse rate is about $5\frac{1}{2}°$ F. loss of temperature for each 1000 feet of altitude.

Adiabatic lapse rate of 70° air

Table 15 shows the adiabatic lapse rate for air that begins its rise from sea level at 70° F.

TABLE 15

THE ADIABATIC LAPSE RATE IN TEMPERATURE IN DEGREES CENTIGRADE AND FAHRENHEIT, WITH ALTITUDE IN FEET ABOVE SEA LEVEL, FOR AIR THAT IS AT 70° F. AT SEA LEVEL

ALTITUDE	TEMPERATURE	
18,000	− 34.7° C.	− 30.4° F.
16,000	− 28.4° C.	− 19.0° F.
14,000	− 22.1° C.	− 7.7° F.
12,000	− 15.8° C.	3.5° F.
10,000	− 9.5° C.	14.8° F.
8,000	− 3.3° C.	26.0° F.
6,000	2.9° C.	37.2° F.
4,000	9.0° C.	48.2° F.
2,000	15.1° C.	59.2° F.
0	21.1° C.	70.0° F.

Table 15 is read as follows: Air that happens to be at 70° F. at sea level and that is dry enough to be carried aloft without condensation of moisture (explained on page 459) will have a temperature of 59.2° F. at 2000 feet, of 48.2° F. at 4000 feet, and so on.

Adiabatic chart

A lapse rate may be represented as in Figure 261. In this figure distances along the base line represent temperature, and vertical distances represent altitude. Slanting line *AB* in the chart represents the adiabatic lapse rate of air that is at 70° F. at sea level.

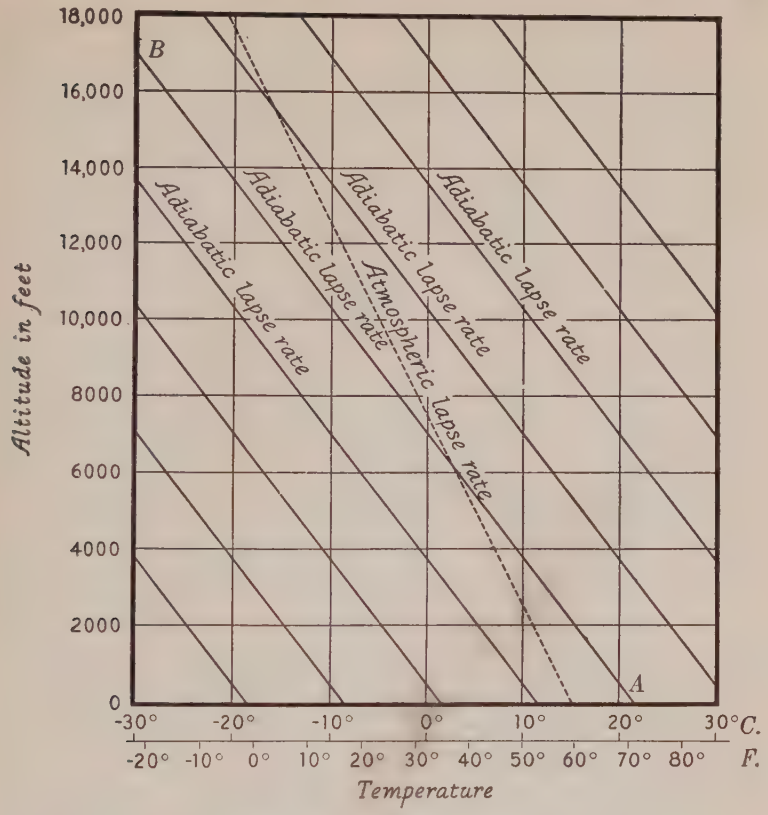


FIG. 261. Adiabatic chart.

Adiabats

The lines parallel to line *AB* also represent adiabatic lapse rates; but they show the adiabatic lapse rates[1] for bodies of air which at sea level had temperatures other than 70° F.

Any line representing an adiabatic lapse rate is called an *adiabat* (ăd′ĭ-*a*-băt).

[1] One might get the impression that the rate of change in temperature in terms of number of degrees per thousand feet is the same in each case, but in speaking of temperature lapse rates we consider the separate lines as separate rates. Actually the rates represented by the several adiabats differ very slightly in slant.

Free circulation of air

We have learned how air tends to expand and cool as it circulates upward and to be compressed and warmed as it circulates downward. Thus four bodies of air, *A*, *B*, *C*, and *D*, circulate as shown in Figure 262; while portion *A* is sinking to position *B* and being compressed and warmed, portion *D* (same amount of air) is rising to position *A* and being expanded and cooled by exactly the same amounts; while portion *C* is rising to position *D* and being expanded and cooled, portion *B* is sinking to position *C* and being compressed and warmed exactly the same amounts. Hence the total amount of heat in the system is the same throughout the circulation; but at all times the air in position *A* is most expanded and coolest, and the air in position *C* is at all times most compressed and warmest.

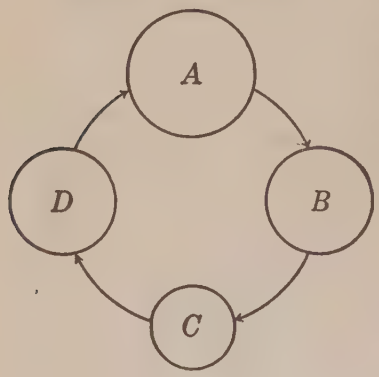


FIG. 262.

These four bodies of air are in equilibrium; and if left to themselves they would tend to come to rest, and no one body would tend to push any other.

The atmosphere tends to be cooler and cooler as we go higher and higher, because of the tendency of air to cool as it expands in rising and to warm as it is compressed in sinking.

General atmospheric lapse rate

Because of the free circulation of the atmosphere, we should expect the change of temperature from layer to layer of air as we go up through the atmosphere to be the same as

the adiabatic lapse rate — the change in temperature of a body of air as it is lifted from one altitude to another. There are reasons, which we shall consider later, why this is not so. We know the adiabatic lapse rate to be about $5\frac{1}{2}°$ F. loss in temperature for each 1000 feet gain in altitude; but as we go up through the atmosphere we find, upon actual observation, that the thermometer drops only about 3° F. for each rise of 1000 feet. This lapse rate we may call the *general atmospheric lapse rate.*

Standard air

Air that has this particular average lapse rate, beginning with 59° F. at sea level, is called *standard air.* Actually, at any particular locality the air is almost never quite standard.

Table 16 shows the temperature, pressure, and density of standard air at various altitudes, as given in the Civil Aeronautics Bulletin No. 26 of the United States Department of Commerce.

TABLE 16

SHOWING THE AVERAGE TEMPERATURE, PRESSURE, AND DENSITY OF STANDARD AIR AT VARIOUS ALTITUDES

ALTITUDE, IN FEET	TEMPERATURE		PRESSURE, IN INCHES OF MERCURY	DENSITY, IN SLUGS PER CUBIC FOOT
	Cent.	Fahr.		
50,000	− 55	− 67.0	3.44	.000361
40,000	− 55	− 67.0	5.54	.000582
30,000	− 44.5	− 48.0	8.88	.000889
20,000	− 24.6	− 12.3	13.75	.001267
15,000	− 14.7	5.5	16.88	.001496
10,000	− 4.8	23.3	20.58	.001756
8,000	− 0.8	30.5	22.22	.001869
6,000	3.1	37.6	23.98	.001988
4,000	7.1	44.7	25.84	.002112
2,000	11.0	51.9	27.82	.002242
0	15.0	59.0	29.92	.002378

The average values of temperature and pressure in Table 16 have been obtained by many observations. The corresponding values of the density are obtained as shown in Problem 4 by means of the formula,

$$\text{Density} = .02288 \frac{\text{Pressure}}{\text{Absolute temperature}},$$

in which Density is in slugs per cubic foot and Pressure is in inches of mercury.

PROBLEM 4. What is the density of air at 10,000 feet, if the pressure at that altitude is 20.58 inches of mercury and the temperature is − 4.8° C., as shown in Table 16?

SOLUTION. 1. − 4.8° C. = 273° A. − 4.8° = 268.2° A.

2. Pressure = 20.58

3. $$\text{Density} = .02288 \times \frac{20.58}{268.2}$$
$$= .02288 \times .07673$$
$$= .001756$$

The density at 10,000 feet is .001756 slug per cubic foot because of the pressure and temperature attained at that altitude.

EXERCISE 6. What is the density of the atmosphere at 15,000 feet, if the pressure at that altitude is 16.88 inches of mercury and the temperature is − 14.7° C.? Check your answer with Table 16.

Relation between general and adiabatic lapse rates

The general atmospheric lapse rate is shown by the dotted line in Figure 261.

The adiabatic chart (Fig. 261) shows clearly that as a body of air is carried or pushed up through the atmosphere its temperature decreases more rapidly than does the temperature from layer to layer of the atmosphere. Or, to put it the other way, as we go up through ordinary atmosphere (as represented by the dotted line) we find the decrease in

temperature from altitude to altitude to be less than the decrease in temperature of a body of air lifted from altitude to altitude. You will see the reason for this when we discuss the effect of condensation of water vapor.

Next we need to consider unstable air, its relation to adiabatic lapse rates, and its effect upon the weather.

Questions

1. What instrument is used to measure pressure?
2. Describe a mercury barometer.
3. About how high does the mercury stand in a barometer?
4. What is measured in millibars?
5. The pressure of one inch of mercury equals about how many millibars?
6. Does the pressure diminish the same amount each 1000 feet as we go up in the atmosphere?
7. If the temperature of a gas is constant, what relation exists between volume and pressure?
8. How do the Centigrade and the Fahrenheit thermometers compare?
9. How do you change Fahrenheit to Centigrade? Centigrade to Fahrenheit?
10. What is Absolute temperature?
11. How could you change Centigrade to Absolute?
12. If a given quantity of gas is held at a constant volume, what relation exists between pressure and temperature? In what units is the temperature expressed in this relation?
13. If a given quantity of gas is held at constant pressure, what relation exists between volume and temperature?
14. Can you state which law is Boyle's law, which is Charles's law, and which is Gay-Lussac's law?
15. What formula combines the three laws?
16. What happens to the volume of air that is lifted in the atmosphere? What causes this change?
17. What happens to the density of air as it is lifted in the atmosphere?

18. What happens to the temperature of air that is lifted in the atmosphere?
19. What happens to the temperature of air that is sinking in the atmosphere?
20. What is meant by a temperature lapse rate?
21. What is an adiabatic process?
22. What is an adiabatic lapse rate?
23. What is an adiabatic chart?
24. What is an adiabat?
25. What is meant by the general atmospheric lapse rate?
26. How does the general atmospheric lapse rate compare with the adiabatic lapse rate of air at the same temperature at sea level? About what change in temperature occurs per 1000 feet in each?

32

STABLE AND UNSTABLE AIR

WE SAW in Figure 261 on page 445 that the line representing the atmospheric lapse rate is steeper than the lines representing the adiabatic lapse rates.

If the whole atmosphere could be thoroughly stirred and thus made as uniform as possible, the relatively warmer air at the top and the relatively cooler air at the bottom would then be equally distributed and the atmospheric temperature lapse rate would be an adiabatic lapse rate. In that case we might say that we had "adiabatic atmosphere."

What we actually have, however, is an atmosphere that at the bottom is relatively cooler and higher up is relatively warmer than "adiabatic atmosphere." We might say that the higher we go up in the atmosphere the warmer it becomes relative to "adiabatic atmosphere."

Stable liquid

Suppose we had a pail containing a heavy liquid like honey or molasses at the bottom, water at the middle, and a layer of thin oil at the top. The heavy liquid tends to stay at the bottom, and the light oil tends to stay at the top. We would say, therefore, that the liquid is *stable* — it "stays put."

Stable air

Air that is cooler than adiabatic air is more dense and air that is warmer is less dense. Hence air that has the general atmospheric lapse rate is more dense at the bottom than thoroughly mixed air and less dense high up than

thoroughly mixed air. In other words, it is like the pail of liquid which is stable. It also tends to "stay put"; hence we call it *stable air.*

Unstable liquid

Let us suppose that we have a pail with horizontal partitions dividing it into three sections, and that there is light oil in the bottom section, water in the middle section, and a heavy liquid in the top section. Suppose we draw out the two partitions. The heavy liquid begins to sink immediately and the light oil begins to rise. We say that the liquid is *unstable.*

Unstable air

Similarly, we can have *unstable air.* A given mass of air is unstable when it is less dense at the bottom than it would be if thoroughly mixed, or when it is more dense at the top than it would be if thoroughly mixed. It is unstable because any relatively less dense air at the bottom of a mass of air begins immediately to rise through the mass of air, and because any relatively denser air at the top of a mass of air begins immediately to sink through it.

How air becomes unstable

According to Gay-Lussac's law, if the pressure on a body of air is held constant and its temperature is increased, its volume increases in proportion to the increase in temperature. And if a body of air increases in volume it becomes less dense; that is, it has fewer slugs per cubic foot.

Now let us suppose a body of air near the earth to be warmed by contact with the surface. The pressure of the atmosphere upon this body of air is caused by the weight of the air above it. The warming of the air near the surface does not change the weight of the air above it. Hence

this air near the earth has its temperature increased while its pressure is held constant. The volume of that body of air increases, therefore, and it consequently becomes less dense than the surrounding air.

Such a body of air is pushed up in the atmosphere for the same reason that a cork released at the bottom of a pail of water is pushed up to the top.

Thermal currents and turbulence

When relatively less dense air at one altitude tends to be pushed up to a higher altitude and the surrounding air consequently sinks, we have vertical currents of air. These are called *thermal currents.* Air that contains thermal currents is said to be *turbulent.* Air that has a tendency to produce thermal currents is, of course, unstable air.

Not all turbulence is produced by thermal currents, however. Another type of turbulence is caused by wind blowing over rough terrain.

Graphic representation of unstable air

Let us assume that the air at a given locality has the lapse rate represented by line *AB* in Figure 263.

Let us assume that the air near the surface is warmed from 15° C. up to 25° C. If the air above 2000 feet could remain stationary while this happened, the lapse rate of the atmosphere below 2000 feet might then be somewhat as shown by the dotted line *CD.*

The surface air has now become much less dense than before it was warmed; and the relatively denser air above forces its way down to the surface and pushes up the warmer lighter air, very much as water at the top of a pail sinks through and forces up a layer of thin oil at the bottom.

When the surface air has been pushed up to 2000 feet it has cooled adiabatically, but only to the temperature repre-

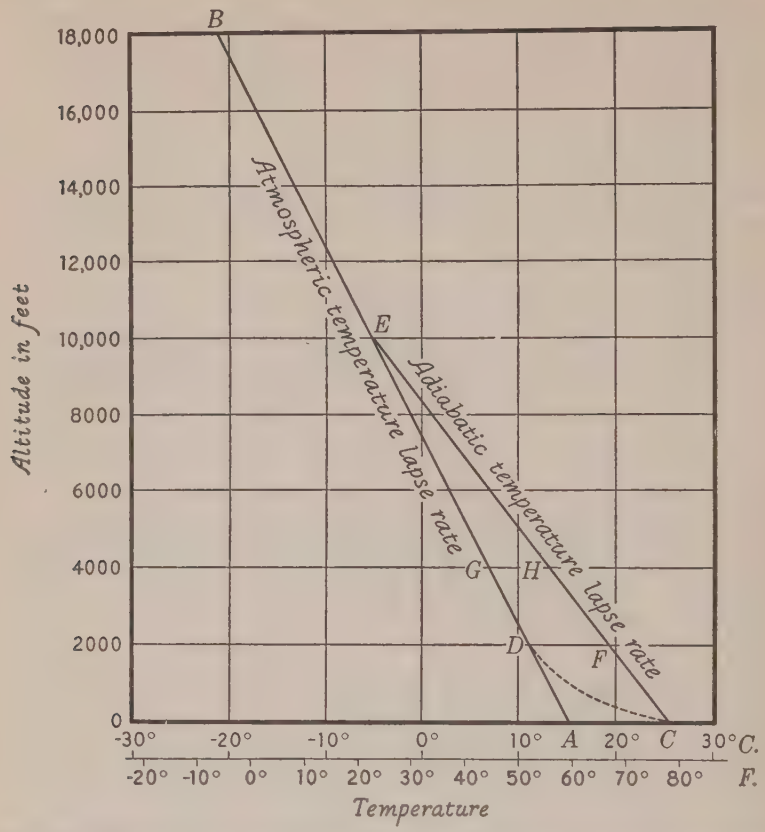


FIG. 263. Graphic representation of air, made unstable by surface heating.

sented by point F in the figure. It is yet warmer than the surrounding air at that altitude which has the temperature shown by D. It still remains less dense than the surrounding air, and therefore it continues to be pushed up.

Limit of turbulence

This process continues until the air that was at the surface has reached the altitude of point E, where the adiabat from C intersects the atmospheric lapse rate line AB.

We see from this illustration that whenever any portion of the general atmospheric lapse rate line (as *CD*) becomes less steep than an adiabat, there is instability. In other words, if an adiabat drawn upward from any point (as *C*) on the atmospheric lapse rate line passes to the right of any portion of the atmospheric lapse rate line (as *CDE*), there is instability. The instability exists for as much of the atmosphere as is represented by the atmospheric lapse rate line that is to the left of the adiabat.

Turbulence in lower altitudes

Surface air warms only gradually; and with only moderate increases in the temperature of the air at the surface, the turbulence resulting from thermal currents extends to only moderate altitudes.

Relativity in warmth

Air like that represented by point *H* in Figure 263, which has risen from the surface where it had the temperature represented by *C*, is often spoken of as "warm air," because it is warmer than the surrounding air, which has the temperature represented by point *G*. The air represented by *H* is actually colder than the air represented by *A*. It would be more precise to speak of the air represented by *H* as "relatively warm" air, meaning *warm relative to the surrounding air at the same altitude.*

There will be occasion for a further discussion of instability after we have considered, in our next chapter, the nature of temperature lapse rates in air that becomes saturated.

Questions

1. Illustrate what is meant by stable air by comparing it to a stable liquid.
2. Illustrate what is meant by unstable air by comparing it to an unstable liquid.

3. How does air come to be unstable?
4. What is meant by thermal currents? by turbulence?
5. What kind of line on an adiabatic chart represents stable air? unstable air?
6. Why might the atmosphere at a given locality be turbulent up to 5000 feet but not above that altitude?

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CLOUD FORMATION AND PRECIPITATION

ALMOST all air in its natural state has in it some water vapor — water in the form of a gas. This vapor has come from the evaporation of water into the air from lakes, rivers, the ocean, etc.

Vapor capacity

At a given temperature and pressure, air can hold only so much water vapor. For example, air at sea-level pressure, at 68° F., can hold only 15 grams of water vapor per kilogram of dry air. That is its *vapor capacity.*

Grams and kilograms

A gram (g.) equals about $\frac{1}{28}$ of an ounce. A kilogram (kg.) equals 1000 grams, or about 2.2 pounds.

The air at sea level at 68° F., therefore, has a vapor capacity of about 1.5 per cent of water vapor by weight.

Vapor capacity varies with temperature

Figure 264 shows the vapor capacity of air of various temperatures at the pressure of sea level and at the pressure of 10,000 feet altitude in standard atmosphere. Point *P* shows that at 10° C. (50° F.) air can hold about 8 grams of water vapor per kilogram of dry air at sea-level pressure. Air at − 30° C. at sea-level pressure can hold only about .3 gram per kilogram.

Warm air can hold a great amount of water vapor, relatively speaking, whereas cold air can hold only a very little water vapor. The colder air becomes the less vapor it can hold.

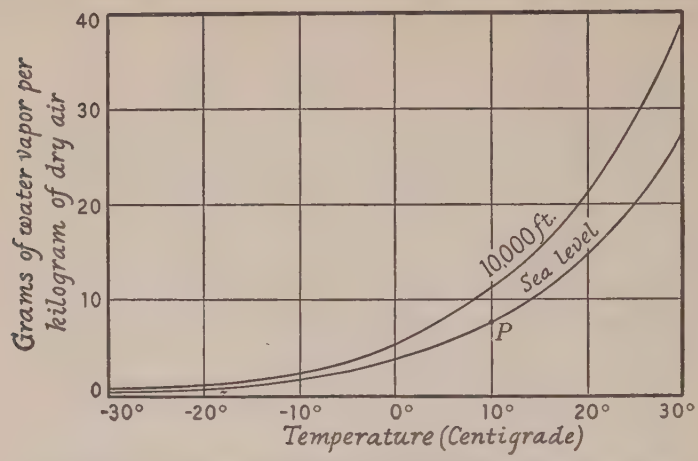


FIG. 264. The vapor capacity of air at various temperatures, at sea level, and at 10,000 feet.

Vapor capacity varies with pressure

At a given temperature air can hold more water vapor at a low pressure than at a high pressure. Thus, air at 68° F., at sea-level pressure, can hold about 15 grams per kilogram; but air at 68° F., at 18,000 feet, when the pressure is about one-half sea-level pressure, can hold about 29 grams per kilogram.

Saturation of air

Air that contains all the water vapor it can hold is said to be *saturated*. If a sponge is partly full of water and you gradually squeeze it, there comes a time when its capacity is no greater than the amount of water it contains. It is then saturated — holding all it can — and if you squeeze it still more, water will begin to fall out. So it is with air; that is, cooling air is somewhat like squeezing it. It is as if, after reaching saturation, the cooling squeezed water out of the air.

Condensation

If you fill a pitcher with water, place ice in the water, and gently stir it, so as gradually to cool the water and the pitcher and the air in contact with the pitcher, you will notice in a few moments that moisture forms on the outside of the pitcher. This moisture is called *dew*. The cooling of the surrounding air reduces its vapor capacity to a point where the air becomes saturated; then continued cooling "squeezes out" some of the moisture. The formation of dew, as on a pitcher of cold water, is called *condensation*.

Dew point

The temperature at which dew forms is called the *dew point*. If you performed the experiment gradually enough so that the temperatures of the water and pitcher and air were kept close together, and if you measured the temperature of the water the moment dew began to appear on the pitcher, this temperature would be approximately the dew point of the air in the room.

Graphic representation of vapor capacity

The nearly vertical lines in Figure 265 show the vapor capacity of air at various temperatures and pressures. The line marked ⑧ shows that air at sea-level pressure has a vapor capacity of 8 grams per kilogram, if its temperature is between 10° C. and 11° C.; whereas, at the pressure of 18,000 feet, air can have a vapor capacity of 8 grams per kilogram at about 1° C. The other lines show in a similar manner the conditions under which air has a vapor capacity of 2 grams, 4 grams, and 16 grams per kilogram.

Latent heat of condensation

Let us suppose that a body of air is being lifted in the atmosphere. If the air has been cooled by the lifting until

the dew point has been reached and the lifting and cooling are continued so that dew is formed, the condensation of the water vapor into droplets of water gives off heat. The more the air is lifted and cooled, the more condensation takes place and the more heat is liberated. This heat is called the *latent heat of condensation.* Latent means hidden, and the heat is hidden in the water vapor until it condenses. It takes heat to boil water or to make it evaporate in any manner, and this heat is stored in the water vapor, to be liberated when the process of evaporation is reversed and the vapor returns to the liquid state.

Cooling by lifting is slowed

The latent heat that is being gradually liberated in the condensation of vapor does not make the air warmer than it was before condensation began. The latent heat is being liberated only while the air is cooling — while condensation is taking place. The heat liberated merely prevents the air from cooling as rapidly as it would otherwise. Hence, if air had been cooling at the rate of $5\frac{1}{2}°$ F. for each 1000 feet of lifting before condensation began, the cooling might be reduced to 4° or 3° or 2° F. per 1000 feet of lifting after condensation began, because of the liberation of latent heat in condensation.

Lapse rate changed

Because the rate of cooling of air is slowed by the liberation of the latent heat of condensation, the adiabatic lapse rate for a given body of air does not continue uniformly beyond the point where condensation begins.

Figure 265 shows an adiabat AB representing the temperature lapse rate of air that is cooling without condensation. Let us suppose that a body of air at sea level has a temperature of 20° C. and a vapor content of 8 grams per kilogram,

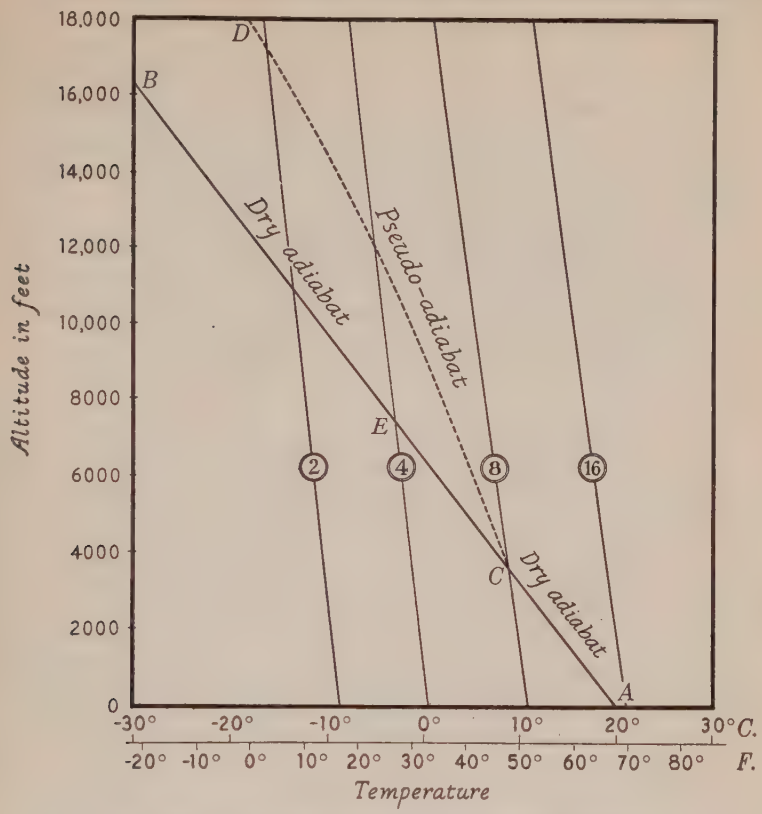


FIG. 265. The use of lines of equal vapor capacity.

and that this body of air will presently be pushed up in the atmosphere. It will cool, as shown by the adiabat *AB*, until it reaches the altitude represented by point *C*, where the adiabat crosses the line representing 8 grams per kilogram. At that point the body of air becomes saturated, because of reduced vapor capacity; hence, as it continues to be lifted and cooled, condensation will take place and the cooling will be at a slower rate because of the liberation of the latent heat of condensation, as explained above. The lesser rate of cooling is shown by the dash line *CD*.

Pseudo-adiabatic process

When saturated air is rising in the atmosphere and is losing its water vapor by condensation and precipitation, the process is characterized as a *pseudo-adiabatic*[1] process. Any line such as *CD* in Figure 265, representing a *pseudo-adiabatic lapse rate*, is called a *pseudo-adiabat.*

A pseudo-adiabatic process is irreversible because, with the water droplets fallen to the earth, the air when it sinks again cannot evaporate the water droplets — it sinks along a dry adiabat, so to speak.

Moist adiabat

When all the moisture condensed in the form of water droplets is carried along upward with the rising air, the temperature lapse rate is slightly different[2] from the temperature lapse rate of rising air that is losing its *condensate* as rain. When all the moisture is carried along, the process is reversible; that is, if the air sinks, the moisture can evaporate back into the air and it will return to its original temperature and vapor content at sea level. When all the moisture is carried along, the resulting adiabat is called a *moist adiabat.*

Dry adiabat

To distinguish the adiabat representing the lapse rate without condensation from the moist adiabat, the adiabat without condensation is called a *dry adiabat.* That does not mean that the air is dry in the sense of having no water vapor. It is "dry" only in the sense that no condensation is going on.

[1] The prefix "pseudo-" (sū′dō) means unreal or resembling. The pseudo-adiabatic process is similar to an adiabatic process but not the same.

[2] The difference lies in the fact that water does not cool off merely by being carried to higher altitudes as air does, and the water droplets that are carried up keep the air from cooling off as rapidly as it otherwise would cool.

The discussion in this book is confined principally to dry adiabats and pseudo-adiabats.

Adiabats start anywhere

Air of any temperature and pressure can be lifted, and it can be either "dry" or saturated. This means that any point on an adiabatic chart may be considered as the beginning of either a dry adiabat or a pseudo-adiabat.

Figure 266 shows a few pseudo-adiabats, to illustrate how their direction differs from the direction of the dry adiabats.

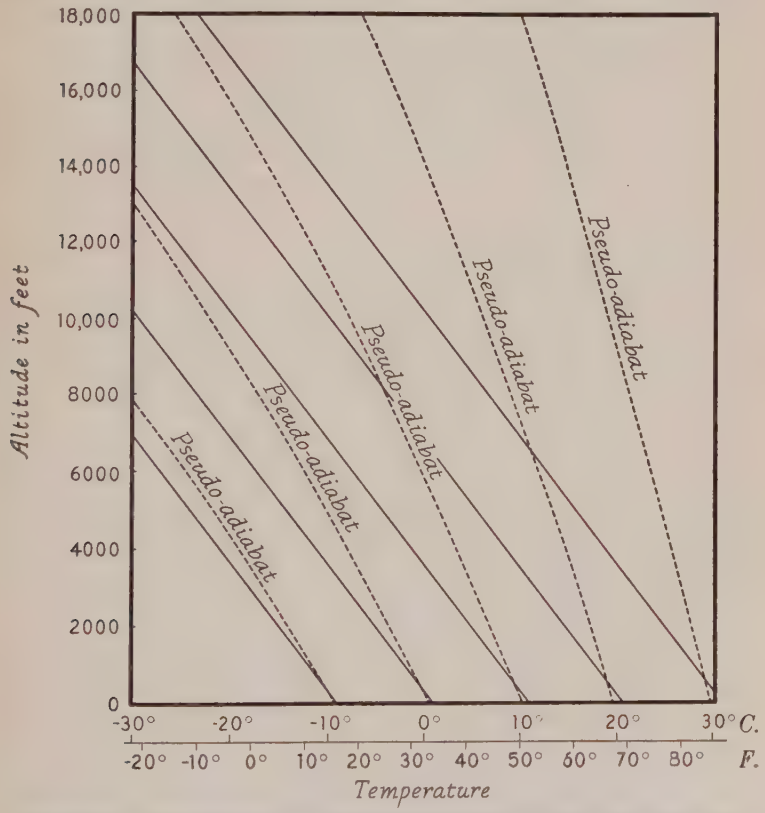


FIG. 266. The difference between the direction of dry adiabats and the direction of pseudo-adiabats.

Cloud formation

Much of the moisture that condenses in rising air often remains suspended in it. This is true especially when the lifting stops before the condensation has proceeded far enough to produce large drops of water. It is by the condensation of moisture and its retention in the air that clouds are formed.

Determination of ceiling

In studying cloud formation it is important to know the height to which air will be lifted before condensation begins. This helps to determine what the *ceiling* will be. "Ceiling," in this connection, refers to the base of a cloud layer. The height to which air can rise without condensation is obtained from the temperature and the dew point.

Significance of the dew point

The dew point of a given body of air is the temperature at which that air would become saturated if cooled without changing its pressure. In Figure 265 the atmosphere at sea level is at 20° C. If the dew point of the air at sea level is 10° C., we would know that when the air is cooled to 10° C. at sea level it will be saturated. The chart shows that air at sea level, at 10°, has a vapor capacity of about 8 grams per kilogram. Therefore, we know that the air at 20° C. at sea level with a dew point of 10° C. has a vapor content of 8 grams per kilogram.

We have already seen that such air can rise to the altitude represented by point *C* in Figure 265 before condensation begins.

Point *C* represents an altitude slightly under 4000 feet; hence if the air at 20° C. at sea level with a dew point of 10° C. is lifted sufficiently, clouds will form at slightly under 4000 feet.

Different dew points

However, if air at 20° C. at sea level has a dew point of 0°, we see from Figure 265 that its vapor content is only 4 grams per kilogram and that it can be raised without condensation to the altitude represented by *E* in the figure, which is about 7500 feet.

The farther the dew point of a body of air is below its temperature, the higher the air can be lifted without condensation.

On the other hand, if air at 20° C. at sea level has a dew point of 19° C., we know that it is almost saturated and that therefore if the air is lifted, condensation will occur almost immediately, forming low clouds amounting almost to fog.

Pilots beware!

If you are about to start on a flight and learn that the temperature of the air along the way or at the destination is only a little above the dew point, beware of fog or low ceiling. On the other hand, if the temperature of air is far above the dew point, the chance of your encountering fog or low ceiling is remote.

Obtaining the dew point

It is quite easy to obtain the dew point of air even though it is not saturated. The meteorologist or airport attendant merely looks at two thermometers, one dry and one with the bulb in a moist cloth which is fanned a few moments before reading the temperature. The temperature read on the moistened thermometer is not the dew point, but it is an indication of the moisture content of the air. The drier the air, the more quickly water will evaporate from the moistened cloth around the second thermometer when fanned, for evaporation has a cooling effect; and hence the lower this second thermometer will read in comparison with

the dry one. By looking in a table, the meteorologist or attendant may obtain the dew point of the air from the two temperature readings.

What happens to heated moist air?

We are now ready to see in more detail what happens when the atmosphere has a given temperature lapse rate and the surface air, having a given vapor content, is heated.

Suppose we let the line *AB* in Figure 267 represent the

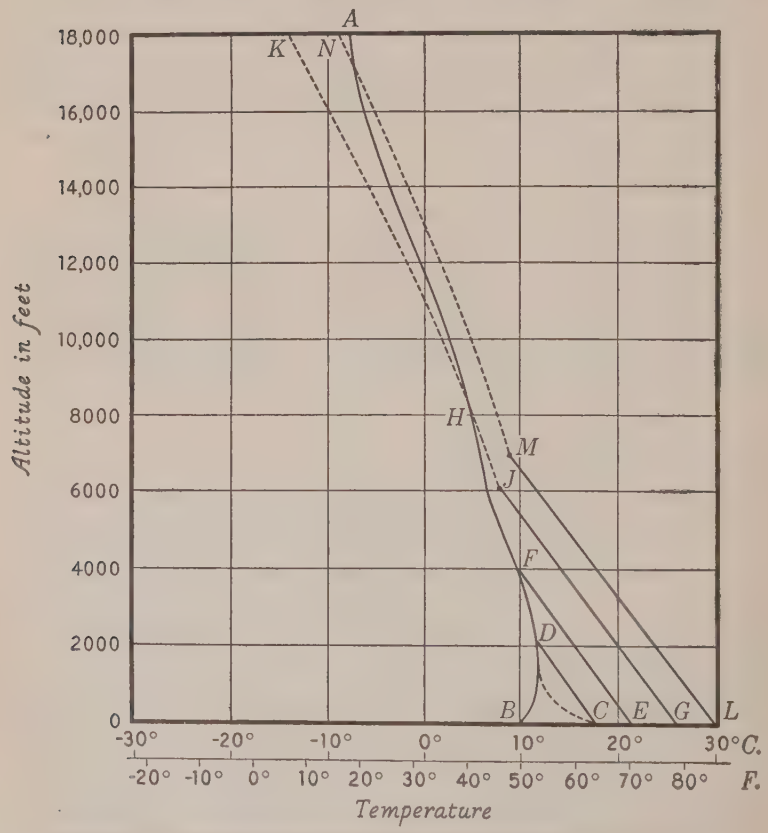


FIG. 267. The rise of heated air and the height of cloud levels.

actual condition of the atmosphere some morning. The air is not standard air as in Figure 263 of Chapter 32, and it shows the effect of surface cooling during the night. In Figure 267 the backward curve at the foot shows the temperature near the surface to be about 10° C. (50° F.). What happens as the sun shines on the ground, warming it, and the heat from the ground warms the air near it?

The first effect of the warming of the surface air will be to bend the curve to the right at the base, as is shown by the dotted line in Figure 267. This movement will cause turbulence in the first 1000 or 2000 feet of the atmosphere, and if we assume that the surface air remains at 17° C. for a while, the base of the curve in Figure 267 will move over eventually to the position *CD*. By that time the air would cease to move if the surface air received no more heat.

But if the surface temperature increases to say 21° C., this will cause more turbulence until the lapse rate of the atmosphere takes the position *EFA*. While this is going on, there will be thermal currents (turbulence) up to about 4000 feet, the air being stable above that altitude.

Now let us assume that the surface air is warmed up to about 26° C. The base of the curve representing the atmosphere is then at *G*, and bodies of air of the degree of lightness represented by the position of *G* can be lifted by the surrounding air along adiabat *GJ*.

Let us suppose the air at *G* to have such a vapor content that it reaches saturation at 6000 feet, at *J* in Figure 267. Point *J* represents a temperature of about 8° C.; and 8° C. would be the dew point at 6000 feet if the air had a moisture content of about 8.5 grams per kilogram.

At *J*, therefore, this air will rise along pseudo-adiabat *JK*, so to speak; that is, it will rise with a slower decrease in temperature, represented by the curve *JK*. But it will rise only up to *H*, for at that altitude (8000 feet) the air from *G* is no lighter than the surrounding air.

We see, therefore, that turbulence in the atmosphere does not ordinarily occur until the sun is high enough to warm the surface air, and that as the surface air is warmed more and more, the height to which turbulence occurs becomes greater and greater.

The formation of clouds; rain

During the rise from J to H, however, condensation is taking place; hence there will be a layer of clouds between 6000 and 8000 feet. If later in the day the surface temperature rises to 30° C. and the air picks up more water vapor from wet earth or bodies of water, this air (from L, Fig. 267), rising along the adiabat LM, may reach saturation at 7000 feet (M). It will reach saturation at 7000 feet (M) if the vapor content has been increased to about 9.5 grams per kilogram. And because the air after saturation rises on pseudo-adiabat MN which is steeper than adiabat LM, the rising air continues to be less dense than the surrounding air until it is pushed all the way up to about 17,000 feet, along the pseudo-adiabat MN.

This means that large "thunderheads" — puffy cumulus clouds — will loom up and rise high in the sky.

As the air cools past the freezing point, ice crystals will form. These may serve as nuclei for raindrops, and we may have precipitation.

Fly high and early for comfort

A good lesson to be learned from this illustration is that in the early hours of the day turbulence is likely to occur only in the lower levels of the atmosphere. Do not be disturbed if the air is rough after the take-off. Go on up to the calm air above and enjoy the ride.

And the earlier the start the longer we can fly before we encounter turbulence. *Daybreak is the best time to start on*

a trip. The next best time to avoid turbulence is late afternoon, when air heating has ceased and turbulence has subsided.

Also we see why *the air is smoother on an overcast day.* The sun cannot warm up the surface air and cause turbulence from thermal currents.

USE OF THE ADIABATIC CHART

Figure 268 shows a portion of a chart of the kind used by meteorologists. This chart differs from the others in this chapter, principally in that the horizontal lines represent various pressures in millibars instead of altitude. Altitude is indicated by the fine dotted lines having a slight slant.

Sea level is represented on this chart by the imaginary horizontal line denoting 1013.3 millibars.

The vertical lines indicate temperature according to the scales at the foot.

The full lines at approximately 45° are the "dry adiabats." Note that particular "dry adiabats" are numbered 303, 313, and so on. These numbers are the Absolute temperatures at which the adiabats cross the 1000-millibar line.

The curved dash lines are the pseudo-adiabats.

The nearly perpendicular lines, numbered 12, 13, 14, and so on, are lines indicating the *vapor capacity* of the air.

Vapor capacity

Note that the line marked 12 on the chart (Fig. 268) passes through the point denoting 800 millibars (mb.) and 13° C. This shows that air at that pressure and temperature has a vapor capacity of 12 grams of water vapor per kilogram of dry air. This means that the air at that pressure, temperature, and vapor content is saturated with water vapor, and that if such air is cooled the vapor will begin to condense. Air represented by any other point on

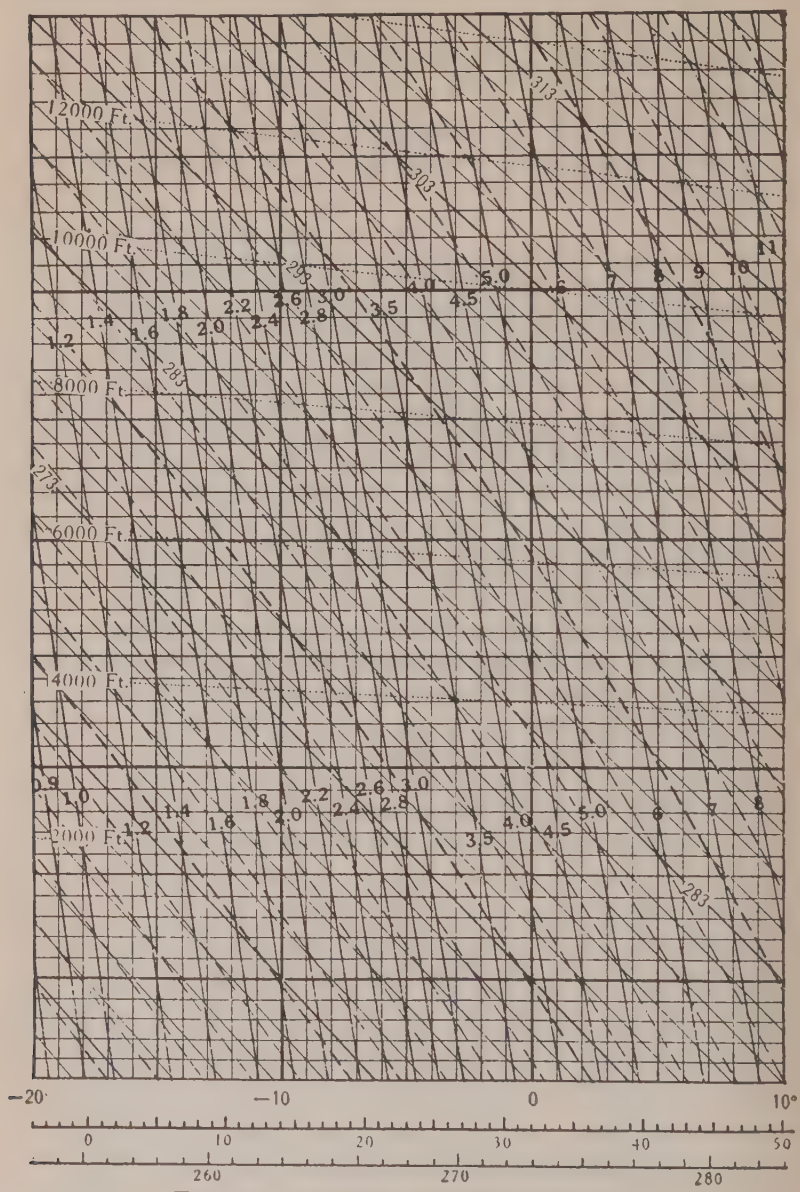
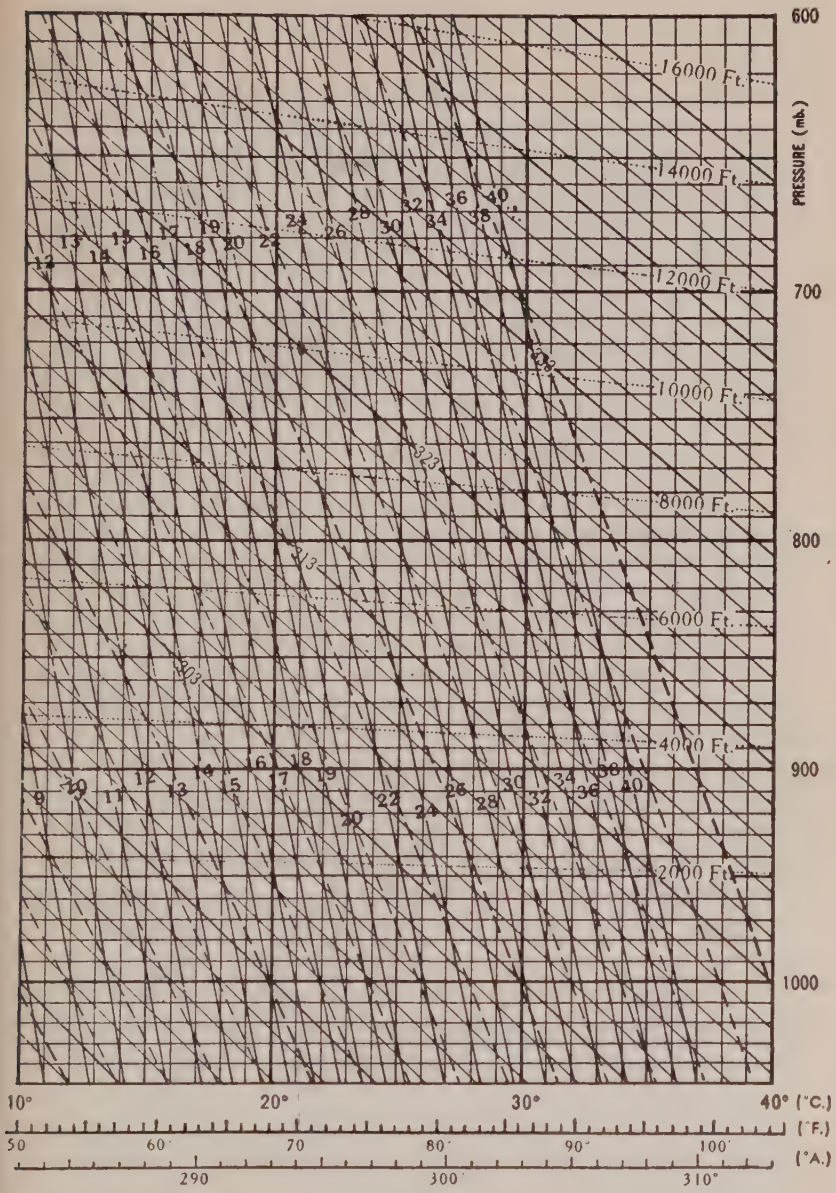


FIG. 268. Meteorologist's adiabatic chart.


600
700
800
900
1000
PRESSURE (mb.)
16000 Ft.
14000 Ft.
12000 Ft.
10000 Ft.
8000 Ft.
6000 Ft.
4000 Ft.
2000 Ft.
10°
20°
30°
40° (°C.)
(°F.)
50
60
70
80
90
100
(°A.)
290
300
310°

that 12-gram line has a vapor capacity of 12 grams per kilogram.

The other vapor-capacity lines have similar meanings.

Be careful to distinguish between *vapor capacity* and *vapor content*. Vapor capacity is the number of grams of water vapor per kilogram that the air *can* hold. Vapor content is the number that the air *does* hold.

Problem 1 illustrates the use of the adiabatic chart.

PROBLEM 1. If a body of air at 294° A. with a pressure of 900 mb. (millibars) has a vapor content of 12 grams per kilogram, how high can it be lifted before condensation takes place?

SOLUTION. 1. 294° A. = 21° C.

2. The intersection of the 21° C. line and the 900-millibar line lies on adiabat 303.

3. This adiabat crosses the 12-gram line at a point representing an altitude of about 6000 feet.

The air can be lifted to about 6000 feet before condensation takes place.

EXERCISE 1. To about what altitude can air be lifted without condensation —

(*a*) if the temperature is 30° C., the pressure is 1000 millibars, and vapor content is 16 grams per kilogram?

(*b*) if the temperature is 306° A., the pressure is 990 millibars, and the vapor content is 28 grams per kilogram?

(*c*) if the temperature is 39° C., the pressure is 970 millibars, and the vapor content is 13.5 grams per kilogram?

EXERCISE 2. A body of air is at 25° C. at 2000 feet. At what altitude will it reach saturation if its vapor content is (*a*) 16 grams per kilogram? (*b*) 12 grams per kilogram? (*c*) 8 grams per kilogram? (*d*) 6 grams per kilogram?

EXERCISE 3. A body of air is at 25° C. at 4000 feet. If no condensation takes place, what temperature Centigrade will it have at (*a*) 6000 feet? (*b*) 8000 feet? (*c*) 10,000 feet? (*d*) 12,000 feet?

EXERCISE 4. A body of air is at 19° C. at 4000 feet. It has a vapor capacity of 13 grams per kilogram. If lifted until it becomes saturated, what temperature will it have?

EXERCISE 5. A cloud layer has its base at 8000 feet, and the air at that altitude has a vapor content of 4 grams per kilogram. (*a*) What is its temperature Fahrenheit? (*b*) What was its temperature Fahrenheit when it was at 2000 feet? (Air at the base of a cloud layer is saturated.)

EXERCISE 6. A body of air was at sea level (1013 millibars) at 294° A. As the air was lifted its water vapor began to condense at 8000 feet. What was its vapor content? At what temperature was it when the condensation began?

Relative humidity

If a body of air at a given temperature has a vapor capacity of 40 grams per kilogram, and has a vapor content of 10 grams per kilogram, the vapor content is 25 per cent of the vapor capacity. We say that the *relative humidity* of that air is 25 per cent.

Specific humidity is another name for vapor content. Be careful to distinguish between *specific humidity* and *relative humidity*. Specific humidity is the quantity of vapor a body of air contains. The relative humidity is the ratio of the specific humidity, or vapor content, to the vapor capacity.

EXERCISE 7. A body of air has a vapor capacity of 30 grams per kilogram. It has a vapor content of 24 grams per kilogram. What is its relative humidity?

EXERCISE 8. A body of air at 19° C. at 4000 feet has a vapor content of 4 grams per kilogram. (*a*) What is its relative humidity? What relative humidity would this body of air have if lifted to (*b*) 6000 feet? (*c*) to 8000 feet? (*d*) to 10,000 feet?

EXERCISE 9. A body of air reached saturation at 10,000 feet at − 1.5° C. What was its relative humidity (*a*) at 8000 feet? (*b*) at 6000 feet? (*c*) at 4000 feet?

Exercise 10. A body of air has a specific humidity of 2 grams per kilogram. It is at 9° C. and 6000 feet. What is its relative humidity, and at what altitude will its relative humidity be 50 per cent?

Problem 2. A body of air is at 29° C. at an elevation of 2000 feet. It has a vapor content of 15 grams per kilogram. If this air is lifted, at what altitude will condensation occur, and what will be its vapor content at 10,000 feet? What per cent of its original vapor content will have been lost?

Solution. 1. The point representing air at 29° C. and 2000 feet lies on adiabat 307.

2. If we follow up this adiabat [1] to the line representing 15 grams per kilogram, we find the intersection to be at about 17° C. and 6000 feet. Condensation will occur at about 6000 feet.

3. This intersection lies also on a pseudo-adiabat (dash line). If we follow up this pseudo-adiabat to the altitude of 10,000 feet, we find the intersection to lie about halfway between the 12-gram and 13-gram lines. At this altitude, therefore, the air has had its vapor content reduced by condensation to about $12\frac{1}{2}$ grams per kilogram.

4. The loss is $15 - 12\frac{1}{2}$, or $2\frac{1}{2}$ grams per kilogram. This is about 17 per cent.

Exercise 11. What would be the vapor content of the body of air of Problem 2 if lifted to 12,000 feet? What per cent of the original water vapor has been lost at this altitude?

Exercise 12. A body of air is at 5° C. at 2000 feet. It has a specific humidity of 2.8 grams per kilogram. At about what altitude will condensation occur if this air is lifted? What will be its specific humidity at 10,000 feet? What per cent of the original water vapor will have been lost at this altitude?

[1] You may find it helpful to use two pins for this work. Place the point of one pin at the first intersection and hold it there while you locate the next intersection with the other pin. It is better not to mark the chart; the marks soon become confusing.

PROBLEM 3. A body of air at 1000 millibars has a temperature of 22° C. and a dew point of 12°. What is its vapor content? At what altitude will condensation occur if this air is lifted? At what altitude will ice clouds or snow form?

SOLUTION. 1. The dew point of air is the temperature of air which is saturated at the same pressure and vapor content. The point on the 1000-millibar line and at 12° C. lies on the 9-gram line. This shows that air at 1000 millibars at 12° C., which air is saturated, has a vapor content of 9 grams per kilogram.

2. The point representing air at 22° C. at 1000 millibars is on adiabat 295. Following up this adiabat to the line representing 9 grams per kilogram, we find the intersection to be at about 4400 feet. Condensation will occur, therefore, at about 4400 feet.

3. The intersection is also on a pseudo-adiabat. Following up this pseudo-adiabat, we find it to intersect the 0° C. line at a point representing an altitude of about 10,500 feet. Hence ice clouds or snow will form at about 10,500 feet.

EXERCISE 13. A body of air is at 10° C. at 1000 millibars. The dew point is also 10° C. If this air is lifted, how soon will condensation begin? At what altitude will ice clouds or snow form?

EXERCISE 14. A body of air at 22.5° C. at 960 millibars has a dew point of 13° C. If this air is lifted, condensation will occur at about what altitude? At about what altitude will ice clouds or snow form?

PROBLEM 4. Assume the atmospheric lapse rate to be uniform and represented on the chart by a straight line from 10° C. at 1000 millibars to − 10° C. at 600 millibars. A particular body of air at 1000 millibars has a temperature of 16° C. and dew point of 12° C.

(*a*) Will the body be lifted in the atmosphere?

(*b*) If so, to what height will it be lifted before condensation?

(*c*) To what total height will it be lifted?

(*d*) Will ice clouds or snow form?

SOLUTION. 1. The particular body of air is warmer than the surrounding air, being at 16° C. as against 10° C. at 1000 millibars. Hence (*a*) it will be lifted in the atmosphere.

2. Air at 12° C. at 1000 millibars has a vapor capacity of 9 grams per kilogram. Since the dew point of the body of air is 12° C. at 1000 millibars, its vapor *content* is 9 grams per kilogram.

3. The body of air at 16° C. at 1000 millibars lies on adiabat 289.

4. Adiabat 289 intersects the 9-gram line at a point representing 11° C. at 940 millibars. This point represents 2000 feet. Hence (*b*) condensation will begin at about 2000 feet.

5. Lay a ruler on the chart from 10° C. at 1000 millibars to − 10° C. at 600 millibars. This represents the atmospheric lapse rate. The body of air is yet warmer than the surrounding air. Its temperature at 2000 feet is 11° C., whereas the temperature of the surrounding air at 2000 feet, according to the atmospheric lapse rate, shown by the ruler, is only about 7° C. Therefore the body of air will continue to rise. It will do so now along a pseudo-adiabat.

6. Following the pseudo-adiabat from the point (11° C. and 940 millibars) to the 0° C. line, we find the intersection to be at a point representing 730 millibars, or an altitude of about 8800 feet. Hence (*c*) ice clouds or snow will form at about 8800 feet.

The body of air continues to be warmer than the surrounding air, and therefore it will continue to be lifted.

7. Following the pseudo-adiabat on up, we find it would intersect the line representing the atmospheric lapse rate (ruler) at a point representing an altitude of about 14,500 feet. Hence (*d*) the body of air will cease to be lifted at about 14,500 feet. Here the temperature of the body of air and of the surrounding air are both about − 9° C., and there is therefore no more lifting tendency. This height, 14,500 feet, might be the top of a cloud layer.

EXERCISE 15. To what height in the atmosphere supposed in Problem 4 would a saturated body of air at 12° C. at 1000 millibars be lifted? Would ice clouds or snow form? If so, at what altitude?

It will be helpful next to consider what general types of air are found in large quantities on the earth and to consider the movement of these "air masses."

Questions

1. What is the source of the water vapor in the atmosphere?
2. What is meant by vapor capacity?
3. How do grams and kilograms compare with each other and with pounds and ounces?
4. Which has more vapor capacity, air of 50° F. at sea level or air at 50° F. at 10,000 feet?
5. Which has more vapor capacity, air at sea level at 50° F. or air at sea level at 70° F.?
6. What is meant by saturated air?
7. What is condensation? dew?
8. What is meant by dew point?
9. How can you find the vapor capacity of air of a given temperature and pressure or altitude by means of an adiabatic chart?
10. What is meant by the latent heat of condensation?
11. What effect does the latent heat of condensation have on the lapse rate of lifted air?
12. What is the pseudo-adiabatic process?
13. What is a pseudo-adiabat?
14. What is a dry adiabat?
15. How do pseudo-adiabats differ in direction from dry adiabats?
16. How many dry adiabats are there, theoretically?
17. What causes cloud formation?
18. What is a ceiling?
19. What is the value of knowing the dew point of air?
20. How does a meteorologist obtain the dew point of air?
21. What is the cause of rain?
22. What is the basis for the statement: Fly high and early for comfort?
23. Would you expect the air to be smoother on a sunny day than on an overcast day? Why?
24. What is meant by relative humidity?
25. How could you find the height to which air in a given locality could be lifted without condensation?
26. How could you find the per cent of water vapor that air would have lost when lifted to a given altitude?

27. How would you find the altitude at which ice clouds would form if air at a given locality were lifted?
28. Is the lapse rate greater or less when there is precipitation than otherwise?
29. What are thunderheads? What causes their formation?
30. What determines whether the clouds formed in rising air will be water clouds or ice clouds?

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AIR-MASS SOURCES AND CHARACTERISTICS

FROM a consideration of the effects of changes in temperature and humidity discussed in the preceding chapter, we are in a position to understand the characteristics of various air masses if we know their sources.

The source of an air mass is the region where it has remained long enough to be fully subjected to the effects of that region.

Polar and tropical air masses

An air mass is classified as *polar* or *tropical*, depending upon whether its source was a polar region or a tropical region.

Continental and maritime air masses

An air mass is classified also as *continental* or *maritime*, depending upon whether its source region lay over land or water.

We have polar continental, polar maritime, tropical continental, and tropical maritime air masses. Since most of the tropical regions south of the United States are maritime, most tropical air masses in the United States are tropical maritime air masses. Polar air masses in the United States may be either polar continental or polar maritime.

Insolation

Heating of the earth's surface by the sun's rays is called *insolation*. Since the sun's rays strike the earth at a steep

angle in the tropics, the insolation is relatively great in that region; and since the sun's rays strike the earth's surface at a flat angle in the polar regions, the insolation is relatively little in those regions.

Terrestrial radiation

Every body, no matter how cold it is, is radiating some heat; and heat is lost by radiation from the surface of the earth into outer space. Radiation from the earth is different in wave length from the radiation received from the sun, and the earth, even though relatively cool, radiates as a whole as much heat as it receives. We know that this is true because otherwise the earth would be getting warmer or colder. But it keeps the same average temperature from century to century; so we know that the total amount of heat lost by the earth in radiation just balances the amount gained by insolation.

At the equator more heat is received than is radiated. This keeps tropical temperatures high. At the poles more heat is radiated than is received. This keeps the polar temperatures low. The excess heat received in the tropics but not radiated there is transferred to the polar regions by means of the general circulation of atmosphere, in which tropical air moves poleward aloft and polar air moves equatorward near the surface.

Polar air

Air received at the poles descends from aloft and is cooled at the earth's surface, thereby becoming cold and having a stable lapse rate. You will remember that air is *stable* when it has a relatively small decrease in temperature with altitude. Hence, air cooled at the bottom becomes stable.

If the source region is a continental area, such as northern Canada, the air will not absorb much moisture and hence will be *cold, stable, and dry;* and those qualities are characteristic of a polar continental air mass.

If the source region is a maritime area, like the North Pacific, the air will have absorbed more water and hence will be *cold, stable, and relatively "moist";* and those qualities are characteristic of a polar maritime air mass. "Moist" in meteorology means, as we have learned, having relatively high humidity — not actually being wet.

Tropical air

Air remaining at the tropics for some time is warmed at the surface and therefore becomes warm and relatively unstable (more nearly unstable). Actually, unstable air is air having a lapse rate greater than the adiabatic lapse rate, as we learned in Chapter 31. Tropical air has a lapse rate close to the adiabatic lapse rate.

Tropical air that remains over a continental area such as Africa tends to be *warm, relatively unstable, and dry,* the characteristics of a tropical continental air mass.

Tropical air that remains over a maritime area such as the Caribbean tends to be *warm, relatively unstable, and relatively moist,* the characteristics of a tropical maritime air mass.

Air masses not pure

It must be remembered that we in the United States do not receive air masses with exactly the characteristics they had at their sources. These characteristics have been modified by the journey of the air from its source region. But even as received in the United States, the various air masses still possess to a considerable extent their original characteristics.

We are now ready to see what happens when air masses from different sources come together.

Questions

1. Into what classes are air masses divided?
2. What is meant by insolation?
3. What is meant by terrestrial radiation?
4. What relation exists between insolation and terrestrial radiation?
5. What are the characteristics of polar air? of tropical air?
6. What are the characteristics of:
   (*a*) polar continental air?
   (*b*) polar maritime air?
   (*c*) tropical continental air?
   (*d*) tropical maritime air?

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AIR-MASS CONVERGENCE — DEFLECTION

IN THE temperate zone cold air often flows down from the north and warm air often flows up from the south; hence it often happens that two air masses of different temperatures meet.

The boundary slants

Suppose you had a pan with a removable partition through the middle and one compartment contained water and the other oil. If you lifted out the partition, the water would sink and push up the oil until the boundary between the two liquids became horizontal.

Similarly, if a cold air mass and a warm air mass meet, the cold air, which is more dense than warm air, tends not to mix with the warm air but to flow under it in the shape of a wedge, thereby creating a slanting boundary. The angle a boundary makes with the surface may be very slight — so slight that the boundary may be only one mile high at a point 100 miles back from where the boundary meets the surface.

Deflection of winds

If the earth did not rotate, wind that started blowing toward the south would presumably continue to do so, and it would be the same with wind blowing toward the north. But the rotation of the earth causes winds to veer to the right in the northern hemisphere and to the left in the southern hemisphere. This veering to the right or left is called *deflection*. To understand the reason for the deflec-

tion of wind, we must consider the effect of the centrifugal force, or momentum, of the air as a result of its movement around the axis of the earth as the earth rotates.

Deflection of poleward-moving air

The earth is revolving so that its surface moves "from west to east," as we say. Take the northern hemisphere. Let us suppose that in a unit of time (as from T_0 to T_1) a meridian moves from the position marked T_0 to the position marked T_1 in Figure 269, and that a body of air has a northward velocity such that it can travel up the meridian from A to B in the unit of time.

The distance BB_1 represents the eastward component of the velocity of the body of air while traveling from A to B

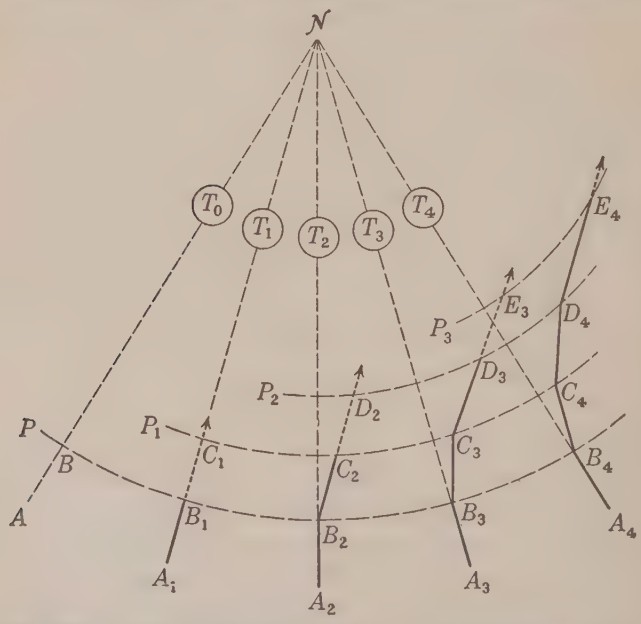

FIG. 269. How the earth's rotation and the rotational momentum of the air tend to cause a northward-moving body of air to be deflected to the right, in the northern hemisphere.

on the meridian; hence the body of air is at position B_1 at the end of the unit of time (the meridian having moved over to position T_1).

At time T_1 the body of air starts out from B_1 in the direction B_1C_1, that is, up the meridian, the distance B_1C_1 being the same distance as AB.

In traveling the second unit of time (from T_1 to T_2) the body of air tends to maintain the same eastward component of motion, or eastward momentum. That is, it tends to move eastward in one unit of time a distance equal to BB_1, shown by C_1C_2 on parallel P_1.

We may say, then, that from time T_1 to time T_2 the body traveled along B_2C_2 with reference to the moving meridian, and it therefore veered to the right of the meridian.

Let us assume that the direction C_2D_2 represents the direction of motion of the air at time T_2, with reference to the meridian along which it started. In other words, we assume that at time T_2 the body of air set out from C_2 to go to D_2 with reference to the meridian ($C_2D_2 = B_1C_1 = AB$).

Again, we assume that the body retains its eastward momentum and therefore tends to move eastward in a unit of time to a position D_3 on a parallel P_2 such that $D_2D_3 = C_1C_2 = BB_1$.

The path of the body of air with reference to the meridian up to time T_3 is represented by the broken line $A_3B_3C_3D_3$, with the body of air moving in the direction D_3E_3 at that time.

Continuing the same procedure, we find that by time T_4 the air has followed the path $A_4B_4C_4D_4E_4$, and so on.

This figure is not entirely correct, partly because curved distances were measured as straight lines, partly because the wind velocity is greatly exaggerated in relation to speed of rotation of the surface of the earth, and partly because the air does not tend to maintain exactly the same eastward

component of motion. But the figure illustrates in a general way how the rotation of the earth does turn a northward-moving body of air toward the east in the northern hemisphere. In the southern hemisphere a southward-moving body of air also is deflected toward the east, as shown at (*a*) in Figure 270.

Deflection of equatorward-moving air

Roughly speaking, in the northern hemisphere, with air moving northward as in Figure 270, we may think of the meridian as lagging behind the air in its eastward rotational motion; whereas, with air moving southward we may think of the *air* as lagging behind the *meridian* in its eastward rotational motion, because as we move toward the equator the meridian moves faster and faster. This lagging of the air causes it to veer toward the west of the meridian.

We now see the reason for the westward deflection of equatorward-moving air, as shown at (*b*) in Figure 270.

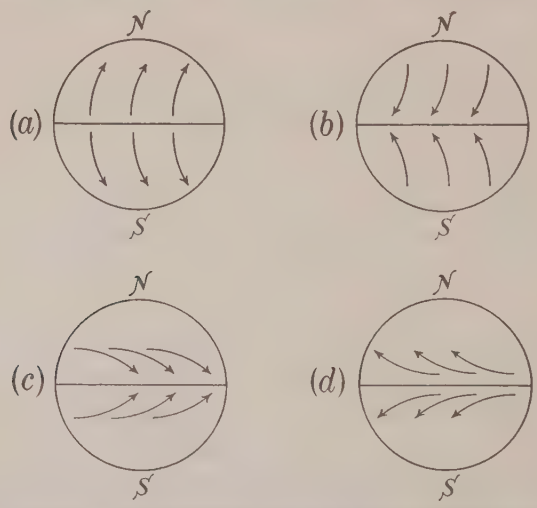

FIG. 270. The deflection of air in the northern and southern hemispheres.

Deflection from eastward motion

The air is held on the earth by the force of gravity acting toward the center of the earth, as shown by vector AG in Figure 271. But the rotation of the earth tends to throw all particles of air off the earth in a plane perpendicular to the earth's axis, as shown by the vector AC.

But this vector (AC) is not vertical (that is, not perpendicular to the earth's surface) but slants toward the equator, E. This means that the centrifugal force of the earth's rotation on every particle of air tends to move it toward the equator.

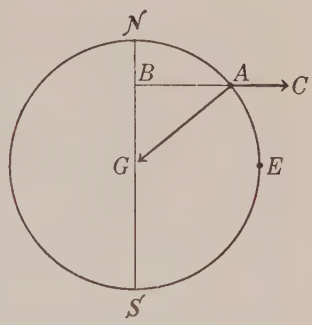

FIG. 271. How the centrifugal force of rotation of the earth tends to force air equatorward.

Now when a body of air is moving toward the east its velocity is added to the rotational velocity of the surface of the earth. This gives it increased centrifugal force and hence a greater force toward the equator. Hence a body of air starting to blow toward the east is deflected toward the equator, as shown at (*c*) in Figure 270.

Deflection from westward motion

When air starts to move west for any reason, its velocity over the surface is *subtracted* from its former eastward rotational velocity; hence its centrifugal force is reduced. This reduces its equatorward component of the centrifugal force. We might say it is not so heavy equatorward. Hence it gets pushed poleward by air that is heavier equatorward, the same as light air gets pushed up by air that is heavier earthward. Hence we see that westward-moving air is deflected toward the poles, as shown at (*d*) in Figure 270.

Deflection to the right in the northern hemisphere

Note how all these causes tend to deflect air to the right in the northern hemisphere, no matter in which way it starts to move; and to the left in the southern hemisphere.

Relative motion of cold and warm air

As cold air comes down from the north it tends to have a boundary or *front* running generally east and west; but owing to the tendency of winds to veer to the right in the northern hemisphere, we find a tendency, at a boundary between cold and warm air, for the air masses to move relative to one another, as shown in Figure 272. That is, the warm and cold air masses tend to move in opposite directions but not perpendicular to the surface boundary line.

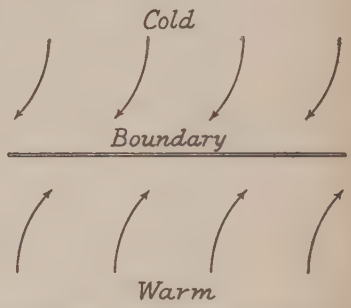

FIG. 272. The relative direction of winds at the boundary between cold and warm air.

Waves

This tendency of air masses to flow toward one another in a direction not at right angles to the boundary causes peculiar phenomena known as *waves*. These waves have a special bearing upon weather which it is important for the airman to understand. The next chapter explains the nature of waves and their bearing upon the weather.

QUESTIONS

1. Do warm and cold air mix easily? Explain.
2. What is the nature of the boundary between cold and warm air masses?
3. What is meant by deflection of winds?

4. In what direction does deflection take place in the northern hemisphere?
5. Can you explain why northward-moving air is deflected?
6. Can you explain why eastward- and westward-moving air is deflected?
7. What is a front?

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WAVE THEORY — WARM AND COLD FRONTS

WHEN two air masses rub against each other, a wave forms that is not quite like a wave in water, but has some of the same characteristics.

The wave theory explains the development and evolution of "fronts." It was originated and developed in Norway by an eminent Norwegian meteorologist, J. Bjerknes, within recent years.

Life of a fully developed wave

Figure 273 shows six stages in the life of a typical, fully developed air wave. Each position of the curve shows the

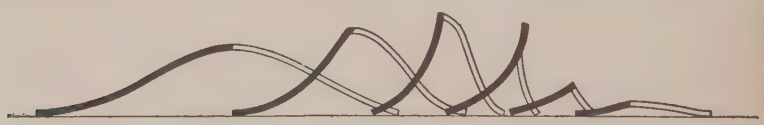


FIG. 273. Stages in the evolution of a wave.

line where the boundary between the cold and warm air meets the ground.

Figure 274 shows a block of plastic molded to show the second of the stages shown in Figure 273.

Figures 275 (*a*) to 275 (*d*) show four stages in the development of the wave. They represent blocks of plastic viewed vertically downward.

We may think of a wave as a wave of warm air projecting downward into the cold air (as shown in Figure 274) — the reverse of a wave of water projecting upward into the air. Remember that in Figure 274 the plastic represents the cold air with the warm air above it.

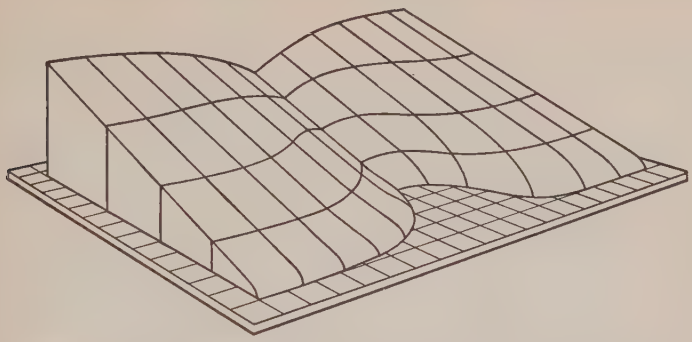


FIG. 274. A model showing how cold and warm air meet in a wave.

Figure 273 shows also how the intersection of the wave and the earth travels along the earth's surface. The speed of movement of the wave in relation to its size varies. Figure 273 is to be considered as diagrammatic only.

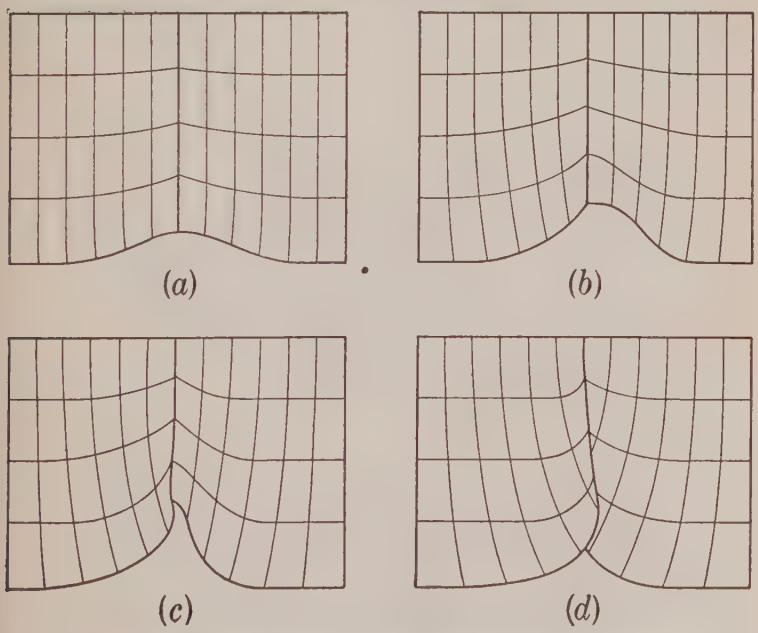


FIG. 275. Four stages in the development of a wave.

Cold and warm fronts

It is important to note that in the wave a portion of the front is where cold air is advancing on warm air (wedging under it). Where cold air is advancing upon warm air, the front is called a *cold front.* This part is shown as a solid black line in Figure 273.

In another portion of the front, cold air is being pushed forward by warm air, or at any rate cold air is receding and warm air is moving in. Such a portion of the boundary is called a *warm front.* A warm front is generally shown as a double light line, as in Figure 273.

A warm front may be thought of as the edge of a cold wedge that is receding. The wave moves in the general direction in which the warm air is moving with reference to the earth, but the wave actually travels more slowly than the warm air mass and therefore, as a wave, it moves along the edge of the warm air in the direction that the cold air is moving.

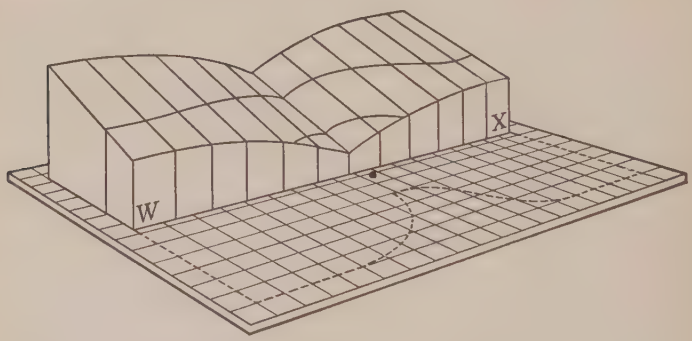
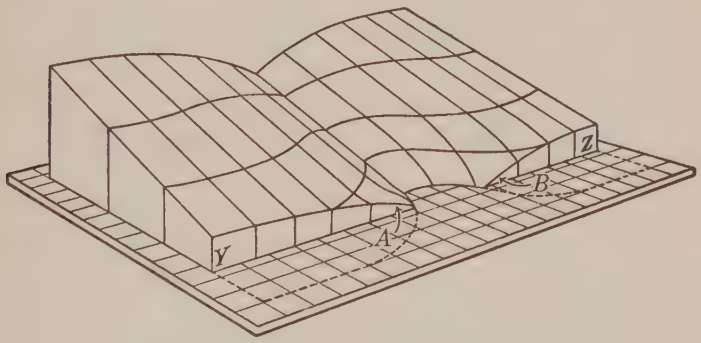


FIG. 276. Cross section of the air at a wave.

Cross section of a wave

Figures 276 and 277 show two vertical cross sections, *WX* and *YZ*, of a typical wave region. Along vertical section *WX* (Fig. 276) all air on the surface is cold, but there is a depression in the warm air above. Along section *YZ* (Fig. 277) warm air comes down to the ground between two fronts, with a wedge of cold air on each side.

Although the general direction of the cold air is to the left, nevertheless at *A* in Figure 277 the front is moving to the right along the ground; hence point *A* is on a cold front. And at point *B* the front is also moving to the right; hence point *B* is on a warm front. (A circle with a dot on it represents the tip of an arrow pointing toward you — out of the page; and a circle with a cross on it indicates an arrow pointing away from you — into the page. These symbols show wind direction at right angles to the line *YZ*.)



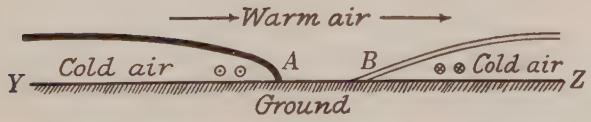


FIG. 277. Cross section of the air at a wave cutting warm and cold fronts.

Occlusion

Note that in the fully developed wave in Figure 275 a valley-shaped depression forms; then gradually the sides of the depression come closer together (one side moving forward faster than the other recedes); and finally one side of the depression seems to fold over the other side. What happens is that some cold air from behind the wave overtakes some lagging cold air in front of the wave and overlaps it, either by climbing up over it or by wedging under it. This overtaking process is called *occlusion*.

If the cold air behind the wave (wave of warm air) is warmer than the cold air ahead of the wave, the faster-moving cold air slides up over the colder air ahead of it, as shown in Figure 278 (*a*).

The lower portion of Figure 278 (*a*) is a vertical cross section of the upper part at the dotted line, and the same in Figure 278 (*b*).

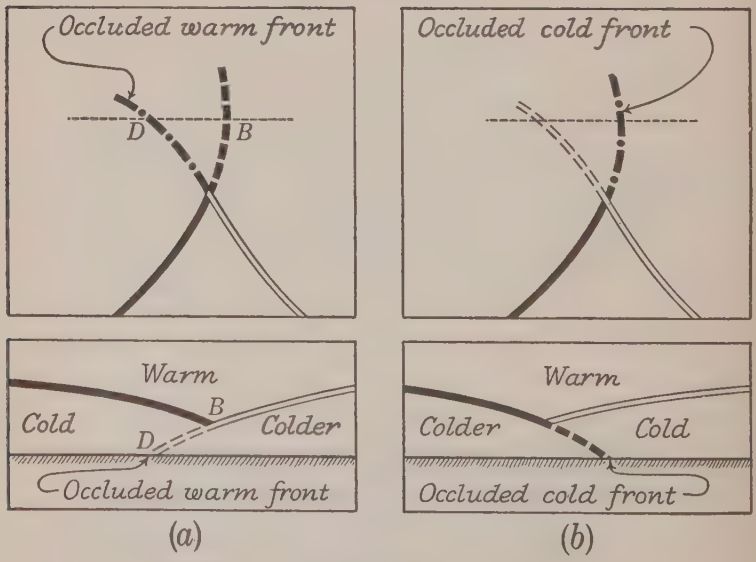


FIG. 278. Occluded warm and cold fronts.

Point *B* in the lower part of Figure 278 (*a*) is what was the cold front but what is now only the front edge of the advancing cold air, which has climbed up over the colder air ahead of it.

Figure 278 (*a*) represents what is called a *warm front occlusion.* The dash-and-dot line in the upper portion is the edge of the receding colder air on the ground. It is what was a warm front but is now covered with cold air (occluded) and is therefore an *occluded warm front.*

If the advancing cold air is colder than the receding cold air when the one overtakes the other, the colder air wedges under and lifts up the less cold air, as shown in Figure 278 (*b*). This type of occlusion is called a *cold front occlusion.* The dash-and-dot line in this figure is the edge of the advancing colder air. It is now an *occluded cold front.*

Stable and unstable waves

Also, it should be understood that not all waves have as complete an evolution as the one shown in Figure 273. Others may have only the first one or two or three stages, then die out. Waves that occlude are called *unstable waves;* those that do not are called *stable waves.*

Motion of air in the vicinity of a wave

The motion of air in and around an "ideal" wave is shown in Figure 279. The arrows in Figure 279 (*a*) show the direction of motion of the air *with reference to the wave.* But the wave is moving (to the right in Figure 279); hence the motion of the air *with reference to the ground* in the vicinity of a wave is not the same as that indicated by the arrows in Figure 279 (*a*).

Let us take, for example, the arrows marked *x* and *y* in Figure 279 (*a*). Arrows *x* and *y* are shown enlarged in Figure 279 (*b*). They are labeled *aw* to indicate motion of the air with reference to the wave. Arrows *wg* represent

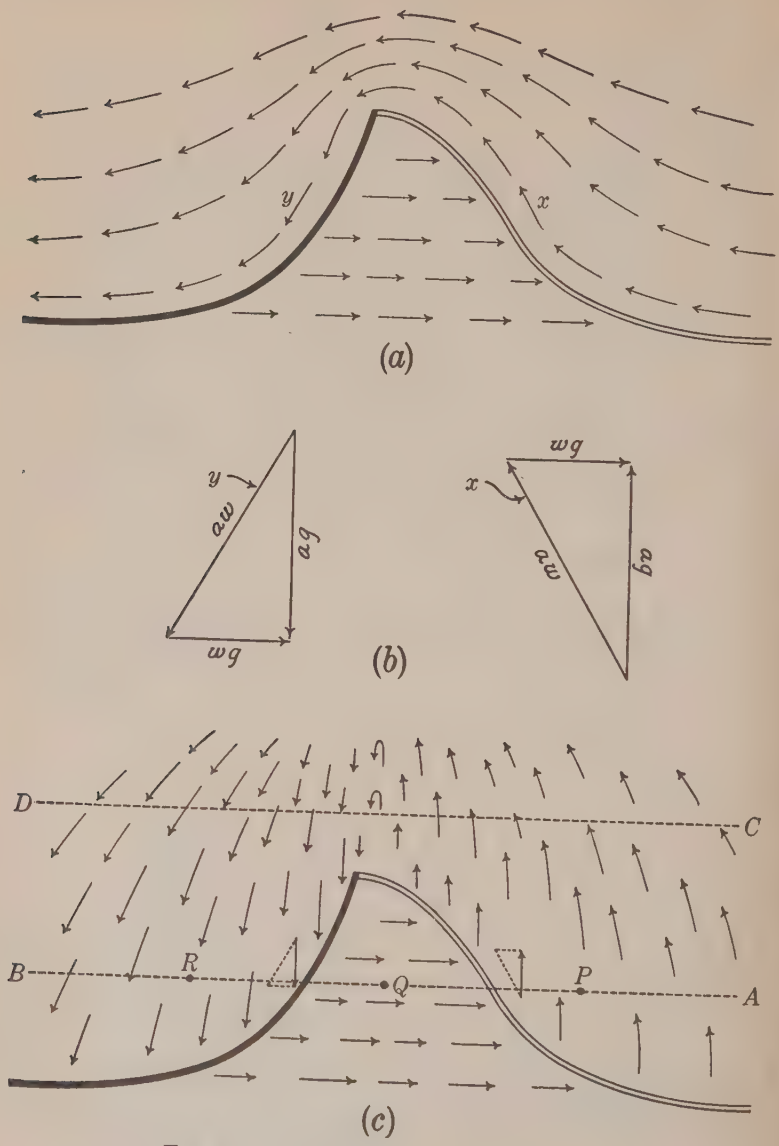


FIG. 279. The motion of air in a wave.

the motion of the wave with reference to the ground. Arrows *ag* represent the resulting motion of the air with reference to the ground.

The arrows in Figure 279 (*c*) show the motion of air with reference to the ground *at the moment* the wave is in the position shown.

Now let us assume that a given locality lies on line *AB*. As the wave passes over the locality it is as if we considered the locality as in successive positions along *AB*, going from right to left. (Let us say that up represents north in this figure.)

We see that as the locality is in position *P* with reference to the wave (warm front approaching), the wind is cold and from the south in this case. When the locality is in position *Q* with reference to the wave (warm front passed), the wind is warm and from the west. When the locality is in position *R* with reference to the wave (cold front passed), the wind is cold again and from the north.

Wind-shift line

We see that the wind shifts rather suddenly as each front passes. A front, therefore, is often called a *wind-shift line*. In fact, wind-shift lines were recognized as such before they were known to be fronts.

If we are in a locality having successive positions such as *P*, *Q*, and *R* with reference to a wave, we experience what we call a wind shift because a cold wind having one direction leaves us and a warm wind having another direction comes to us. Then later we experience another "wind shift" when the warm wind is no longer blowing at our locality but a cold wind having still another direction has come to us. The wind shift in these cases may be thought of as a shift from one wind to another and *not* a shift of direction of the *same* wind.

On the other hand, if we are in a locality having successive positions along the line *CD* with reference to the wave, we also experience a wind shift but for a different reason. In fact, in this case the wind can shift from a south wind to a north wind in a short interval of time; but it will be a cold wind at all times. In this case the same cold air which has blown northward over the locality at one moment may blow southward over that same locality a few moments later. In this case it is more nearly correct, therefore, to think of the wind shift as a shift of direction of the *same* wind.

Ancient meteorologist

It may be that a phenomenon as described above prompted an ancient weather observer to say, as quoted in Ecclesiastes: "The wind goeth toward the north, and turneth about unto the south; it whirleth about continually, and the wind returneth again according to his circuits."

Low or cyclone

Because of the circulatory motion of the air around the apex of the wave, as shown in Figure 279, a centrifugal force is set up which tends to force the air away from the center of rotation. This force is augmented by the force of deflection which causes additional outward force. This outward force produces lowered pressure in the region of the wave, and the area is called a *low*.

Because of its circular motion, the low is also called a *cyclone*.

Isobars

An isobar is a line on a map showing the points on the earth's surface that have the same barometric pressure. (*Iso* = same; *bar* = barometric pressure.) Isobars are anal-

ogous to contour lines, each of which shows points of the same elevation.

Figure 280 shows a *low* caused by a wave, and the manner in which isobars are found in it.

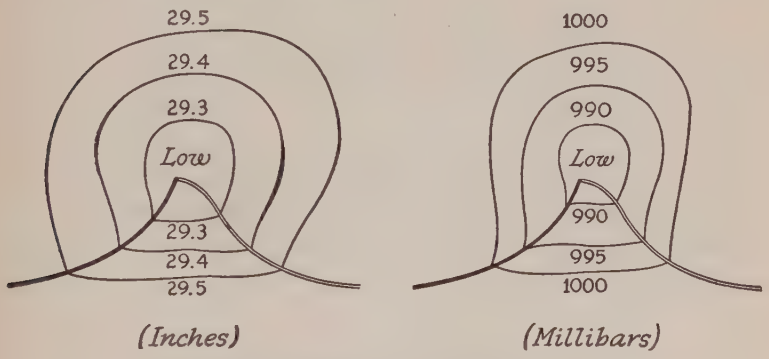


FIG. 280. Direction of the isobars in a low.

A *low* corresponds to a depression in topography such as a dry lake. At all points on the closed curve marked 29.5, the barometric pressure is 29.5 at the surface. At all points on the curve marked 29.4 the barometric pressure is 29.4, and so on. An isobar is always a closed curve (or would be if the map were large enough), the same as a contour line.

It is becoming the custom to determine isobars according to millibars of pressure (as shown at the right in Figure 280) instead of inches.

Note how the isobars form angles at the fronts. To understand why this happens requires an understanding of the relative direction of isobars, pressure gradients, and wind.

Pressure gradient

Figure 281 shows three isobars as more or less parallel curves. The dotted arrows show the direction in which we think of the decrease in pressure as taking place. This decrease in pressure is called a *pressure gradient*. A pressure

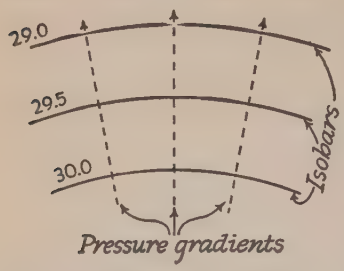


FIG. 281. Relative direction of pressure gradients and isobars.

gradient corresponds to a slanting surface (grade) on the earth's surface. We usually think of the pressure gradient as being at right angles to the isobars, just as we usually think of the direction of "downhill" on a slope as at right angles to the contour lines on a topographic map. Technically, however, a pressure gradient is any line or direction that cuts across isobars, and therefore constitutes a line along which there is a change in barometric pressure.

Wind with reference to pressure gradients and isobars

If a body of air is in a pressure gradient, it has more pressure on one side of it than on the other. Thus, if the pressure gradient extends northward (pressure gets less as we go north), a body of air has more pressure on the south side of it than on the north side and the body of air is pushed in the northward direction by the surrounding air.

But we have seen how air that is being pushed northward is deflected eastward because of the rotation of the earth, and air being pushed eastward is deflected southward, and so on. This means that the body of air represented in Figure 282 tends to move, not in the direction *BG* of the gradient, but in some direction *BD* to which its motion is deflected. In other words, wind tends to blow from

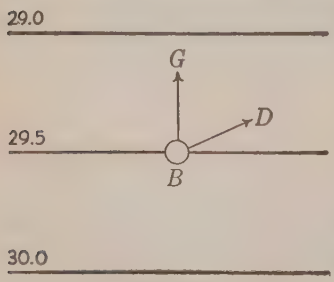


FIG. 282.

high pressure to low pressure, but in a direction deflected toward the isobar.

Winds in a cyclone

In a cyclone the centrifugal force of the rotation and the force of deflection counteract the force of the pressure gradient to such an extent that the wind may blow actually at right angles to the pressure gradient and hence parallel to the isobars.

Thus we see that the direction of wind shown in Figure 279 is approximately the same around the low as the direction of the isobars in Figure 280. And with wind direction tending to be parallel to isobars, and vice versa, it is understood that we get an angle in the isobars at the wind-shift line (front), as shown in Figure 280.

Gradient winds

You have learned that in a *low* the surface winds blow across the isobars at a slight angle; that is, the winds blow slightly inward. Higher up the winds must blow outward, and it has been found that at a certain level above the surface the winds are blowing around the center of the low approximately parallel to the isobars. This level is called the *gradient level.*

The height of the gradient level varies with the roughness of the surface. Over water and smooth terrain the gradient level is about 1500 feet. Over rough terrain it is much higher.

Highs

A weather map often shows a center of isobar rings resembling a *low*, but in which the isobars show increasingly higher pressures toward the center. Such a high-pressure area is called a *high*, or anticyclone. Figure 283 shows a *high* as well as a *low*.

If we think of the isobars as contour lines, a low, as we said, is like a dry lake, but a high is like a large mound, such as a sand dune.

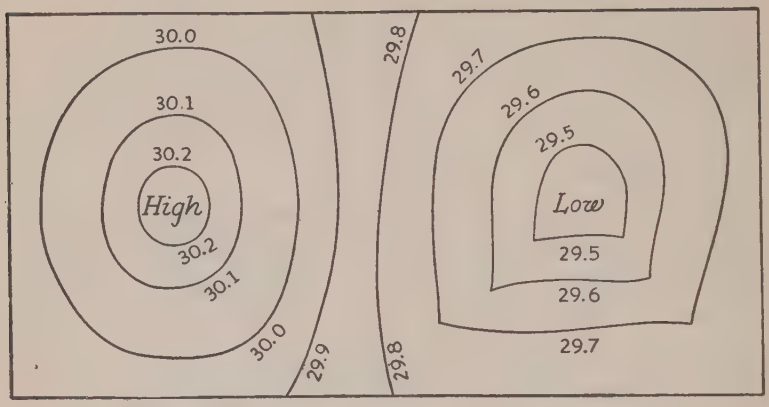


FIG. 283. A high and a low adjacent to one another.

Winds in a low and in a high compared

We have seen that the wind tends to blow from a region of higher to a region of lower pressure — that is, across the isobars down the gradient. This means that the surface wind tends to blow away from the center of a high and toward the center of a low.

But the forces of deflection in the northern hemisphere give the winds a turn to the right which causes them to flow outward from the center of a high with a general clockwise motion, as shown in Figure 284, and inward toward the center of a low with a general counter-clockwise motion.

Buys-Ballot's law

A rule known as Buys-Ballot's law is sometimes used to help one tell, from the direction of the wind, in which way the *low* is. The rule states that "If you stand in the north-

ern hemisphere with your back to the wind — in other words, facing in the direction in which the wind is blowing — the *low* is on your left."

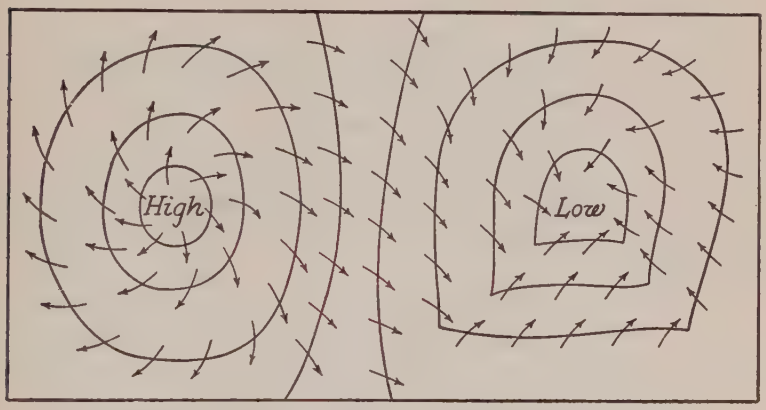


FIG. 284. The winds in a high and a low.

Elevation and subsidence

The air in a *low* tends to rise, especially at the center, and to flow outward from the center, at high altitudes. The air in a *high* tends to sink (subside), especially at the center, and to flow in toward the center, at high altitudes.

Air dry and clear in a high

Since the air in a high is subsiding from high altitudes, and since on rising to high altitudes air loses practically all its moisture, the air subsiding in a high tends to be dry. And because the air is warmed by compression as it sinks, and because warm air has greater vapor capacity than cold air, subsiding air cannot possibly be approaching saturation — it is becoming less saturated. Hence subsiding air in a high is necessarily clear of all clouds.

Clouds can form only where there are rising currents or other causes of cooling, and the right conditions seldom

occur in a high. For this reason we almost always find clear weather in a high.

Cold domes

You should not get the idea from the above discussion of fronts and from Figures 274 to 277 that a boundary between warm and cold air extends up indefinitely. As a rule cold air comes down from the north in large but definite amounts which have been compared to moving mountains. A moving mountain of cold air is called a *cold dome.*

A cold dome might have the shape of a rounded pile of sand, with a cross section as shown in Figure 285. Actually the "dome" is much flatter than is shown in Figure 285.

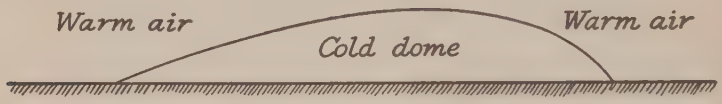


FIG. 285. A cold dome.

It might be 3 miles high and broad enough to cover half the United States, or less than a mile high and 600 miles across.

A cold dome may be slightly scalloped along a portion of its forward edge, with waves forming the indentations. The passing of a cold front may be a case of a cold dome skirting the given locality, so that a wave passes over the locality as described above (Fig. 279); or the dome itself may be passing over the locality. In either case the warm air at the locality is not being pushed up indefinitely but must eventually flow either over a scallop of the dome or over the dome itself and eventually cease to be pushed up.

It is when the warm air ceases to be pushed farther up and begins to subside that all clouds disappear and the air becomes clear. Subsiding air, as explained above, is

becoming warmer and therefore able to hold more water vapor; hence the clouds evaporate.

A thorough understanding of the nature of fronts and the waves that form in them serves as the basis for a great deal of the forecasting of weather conditions which is now possible, as explained in the next chapter.

Questions

1. What is the wave theory in meteorology?
2. Where did the wave theory originate?
3. Can you explain the evolution of a wave as to its path on the earth's surface?
4. What is a cold front? a warm front?
5. What is the relation of fronts to waves?
6. What is meant by occlusion?
7. What is an occluded warm front? an occluded cold front?
8. How do stable and unstable waves differ?
9. Describe the motion of the air in the vicinity of a wave.
10. What is a wind-shift line?
11. What is a low? a cyclone?
12. What are isobars?
13. What is a pressure gradient?
14. In what direction does the wind usually blow with reference to isobars?
15. What is a high?
16. Compare the winds in a high and a low.
17. What is Buys-Ballot's law?
18. What is the usual condition of the sky in a high?
19. What is a cold dome?

37

FORECASTING — CLOUD FORMS

WE HAVE only to realize what is happening to the air over a particular locality as a warm front passes and as a cold front passes in order to forecast the weather for that locality when we know that a cyclone is about to pass it.

Figure 286 shows the cross section of a cyclone in the direction of its motion, say from west to east, as it is shown also in the lower part of Figure 277 of Chapter 36.

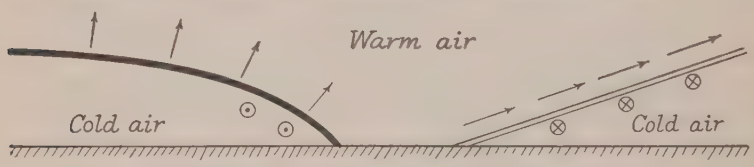


FIG. 286. Cross section of a cyclone.

In the case of the warm front at the right, the warm air, moving faster to the right than the front is moving, climbs up over the cold air as shown by the arrows.

In the case of the cold front at the left, the advancing wedge of cold air pushes the warm air up. In both cases, therefore, we have warm air rising. Let us, therefore, consider what happens when warm air is pushed upward.

Rising warm air

Figure 287 shows what happens when warm, moist air (containing water vapor) is lifted.

(1) The air is cooled by expansion until the dew point is reached (temperature of saturation).

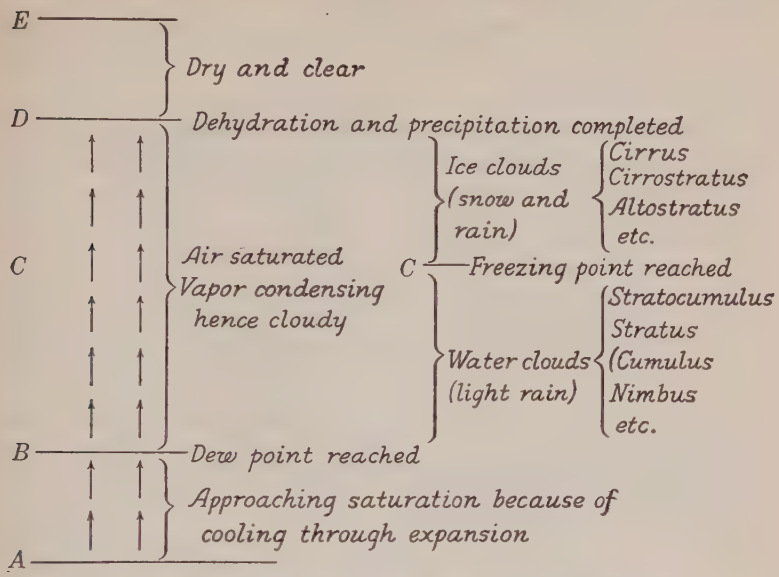


FIG. 287. Changes that take place in lifted moist air.

(2) With continued lifting, expansion, and cooling, condensation of water vapor takes place, forming clouds, with possibly light rain.

(3) With continued lifting, expansion, and cooling, the freezing point is reached (32° F. or 0° C.), and further condensation takes the form of ice-crystal formation or super-cooled droplets.

(4) When ice crystals form at the top of a water cloud, each crystal becomes the nucleus of a raindrop. The water droplets constituting the water cloud begin to collect on these ice crystals. Each crystal begins to descend, collecting such other droplets as it meets on the way down; and thus rain is produced.

(5) In air that is carried upward past the freezing level while condensation is taking place, such condensation is either the formation of ice clouds or water clouds containing super-cooled droplets.

(6) If the condensation of water vapor into ice crystals continues long enough to develop flakes of sufficient size, snow is precipitated.

(7) If the air becomes dehydrated (practically all moisture condensed) and the condensed moisture is precipitated (not carried farther aloft with the pushed-up air), the air becomes "dry" and clear.

Weather with the passing of a warm front

We are now ready to see what happens to the weather in general at a given locality that is in the path of a wave.

First we have the advance of the warm front (receding cold wedge), as shown in Figure 288. The whole picture is moving to the right with reference to the ground.

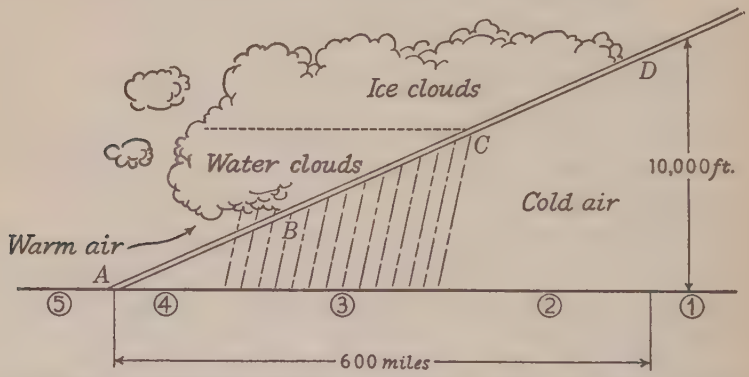


FIG. 288. How weather changes with the passing of a warm front.

(1) When we are in position 1 the sky is clear.

(2) When we are in position 2 there are thin ice clouds high overhead.

(3) When we are in position 3 we have both ice and water clouds above us, and presumably it is raining.

(4) There may be a brief period of fair weather before the warm front passes (in position 4), provided the warm air approaching is sufficiently far below saturation to allow

a moderate lifting before any portion of it reaches its dew point.

(5) When we reach position 5, the warm front (*A*) has passed, the skies become clear, and the weather becomes warm. The wind usually shifts somewhat as the warm front passes (Fig. 279).

(6) While the warm front is approaching and passing, there is a gradual lowering of the barometric pressure (Fig. 289). After the passage of the warm front, the barometer remains low but comparatively stationary.

Weather occurs backward in a sense

You should not be confused when a person says that upon the approach of a warm front, "first high, thin clouds form, and later these change to lower, thicker clouds." Actually the high, thin clouds were lower, thicker clouds that lifted and are fading away. And the lower, thicker clouds never were high, thin clouds; but they may have been still lower and thicker, and they are becoming higher and thinner.

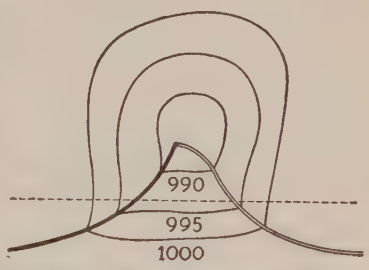


FIG. 289. How barometric pressure changes with the passing of a low.

The point is that we are approaching the cloud formation from the end, not from the beginning. It is as if we were approached by a freight train whose engine smoke was blowing forward faster than the movement of the train, as in Figure 290. First we get the high, thin smoke; then, as the engine approaches, the

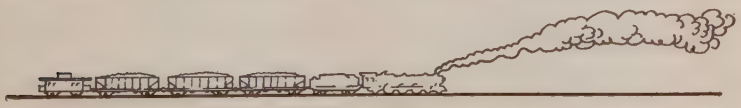


FIG. 290.

smoke that is passing us is lower and thicker. But the high, thin smoke did not become lower and thicker! In the same way, with the passing of a front, high, thin clouds themselves never actually become lower and thicker.

Weather with the passing of a cold front

Figure 291 shows a cross section of an advancing cold front. The angle that the boundary of a cold front makes with the earth, though exaggerated in the figure, is greater than that for a warm front, because friction with the ground retards the motion of the lower layers of cold air in each case. This steepens the boundary of the cold front, but it makes the boundary of a warm front more nearly level.

This steeper boundary of a cold front forces the warm air aloft more rapidly than it climbs up the cold air in a warm front. Also a cold front is usually moving more rapidly than the warm front preceding it. This constitutes another reason for the fact that warm air is lifted more rapidly at a cold front.

In the case of the cold front, in which the lifting of a given body of air takes place during a short interval of time, the rain is necessarily more brief and violent. In fact, rain may fall at a given locality, beginning before the passage of the cold front and continuing until after the passage.

As the cold front passes over a locality (Fig. 291) the weather tends to vary as follows:

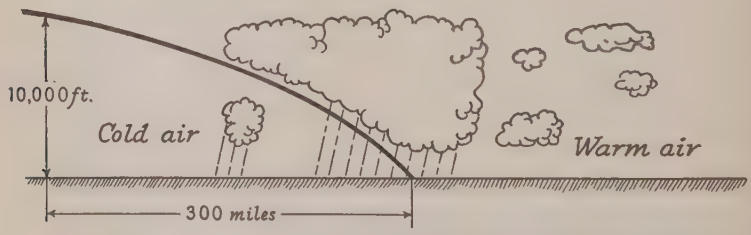


FIG. 291. How weather changes with the passing of a cold front.

(1) First there are scattered clouds. The height of these clouds depends on the height at which the rising mass of warm air was nearest to being saturated.

(2) Later there is rain.

(3) With the passage of the front there is a change from warm to cold air at the surface and a violent shift in surface direction of wind. The barometer begins to show a marked rise in pressure.

(4) Heavy rain continues for a brief period.

(5) Then there is a rather rapid clearing of low clouds, except for cumulus clouds forming in the cold air as a result of warming of the cold air by the warm surface.

(6) Finally there is total clearing, with a blue sky and cold air moving in from behind the front.

Winter frontal passages

In the foregoing description of frontal action we have assumed surface temperatures above freezing. But the same frontal action can take place in winter, except that in winter the temperature may often be below freezing. Then all precipitation will be in the form of snow, or, in rare instances, in the form of freezing drizzle.

CLOUDS

Clouds

Clouds are classified in a variety of ways:

(1) *As to form.* If clouds form in layers (strata) in stable air and remain in layers, they are said to be *stratiform* clouds. If they build up in domes (if they cumulate) with vertical motion relative to surrounding air, they are said to be *cumuliform* clouds.

(2) *As to composition.* A cloud is an *ice cloud* if it consists of ice crystals, or a *water cloud* if it consists of droplets of water.

In general, an ice cloud is high and filmy and is called a *cirrus* cloud. In general, a water cloud is more dense. If a water cloud is in a layer, it is called a *stratus* cloud. If it is cumuliform, it is called a *cumulus* cloud.

(3) *As to altitude.* Clouds are classified as high, middle, or low, according to altitude. Clouds above 20,000 feet are classed as high clouds; those between 6500 and 20,000 as middle clouds; and those under 6500 as low clouds.

(4) *As to precipitation.* Any rain cloud is called a *nimbus* cloud. And we have *cumulo-nimbus* (mountainous cumulus cloud, likely to produce rain or hail — often a thunderstorm).

The following are the most common conventional cloud forms, with their average altitude and the brief description as given in *Cloud Forms* of the United States Weather Bureau:

Cirrus — 33,000 feet. Detached clouds of delicate and fibrous appearance, usually without shading, generally white in color, and often of a silky appearance.

Cirro-stratus — 32,000 feet. A thin, whitish veil which does not blur the outlines of the sun or moon but usually gives rise to halos.

Cirro-cumulus — 27,000 feet. A cirriform layer or patch of white flakes, or globular masses, usually very small and without shadows.

Alto-stratus — 20,000 feet. A striated, fibrous, or smooth veil, more or less gray or bluish in color, like thick cirro-stratus but without halo phenomena; the sun or moon usually shows vaguely with a faint gleam as through ground glass.

Alto-cumulus — 15,000 feet. A layer (or patches) composed of laminae or nearly globular masses.

Stratos-cumulus — 9000 feet. A layer (or patches) of laminae, globular masses or rolls; the smallest of the regularly arranged elements are fairly large; they are soft and

gray with darker parts; also a low, continuous sheet, thick or thin, with distinct irregularities of large size.

Cumulus — 6000 feet. Thick clouds with vertical development; the upper surface is dome-shaped and exhibits rounded protuberances, while the base is nearly horizontal.

Cumulo-nimbus — 4500 feet (base) to 20,000 feet (tops). Heavy masses of clouds, with great vertical development, whose cumuliform summits rise in the form of mountains or towers, the upper part having a fibrous texture and often spreading out in the form of an anvil.

Nimbo-stratus — 3000 feet. A low, amorphous, usually nearly uniform, rainy layer of a dark gray color, feebly illuminated, seemingly from the inside.

What holds the clouds up

You may wonder how droplets of water constituting clouds remain suspended in the air. The secret lies in the fact that their surface is very great in proportion to their weight. To understand this you need to think a moment in terms of geometry.

The volume of a sphere $= \frac{4}{3}\pi r^3$; its surface $= 4\pi r^2$. ($\pi = 3.1416$) The volume of a sphere, therefore, varies as the cube of its radius; the surface varies as the square of the radius. Hence, if you have a sphere of 10-inch radius and decrease its radius to 5 inches (one half as long), you reduce the volume to one eighth its former amount but you make its surface one fourth as large. It now has twice as much surface in proportion to its size as before.

If you reduce the sphere to one with a one-inch radius, its volume is $\frac{1}{1000}$ as much as before but its surface is $\frac{1}{100}$ as much; so the surface is now ten times as great in proportion to its size.

If you reduce the size of a water droplet to $\frac{1}{100}$ its former diameter, you make its surface 100 times as great in proportion to its size as before. The air cannot hold up an

U. S. Army Air Corps

FIG. 292. Cloud forms: Strato-cumulus.

U. S. Weather Bureau

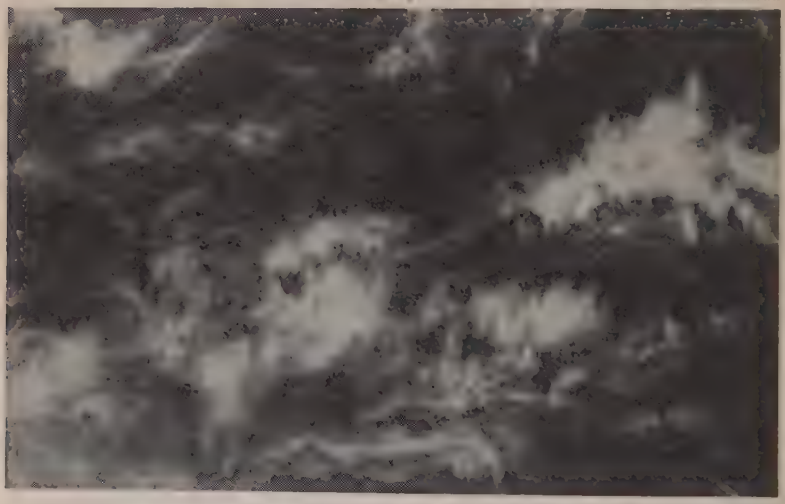


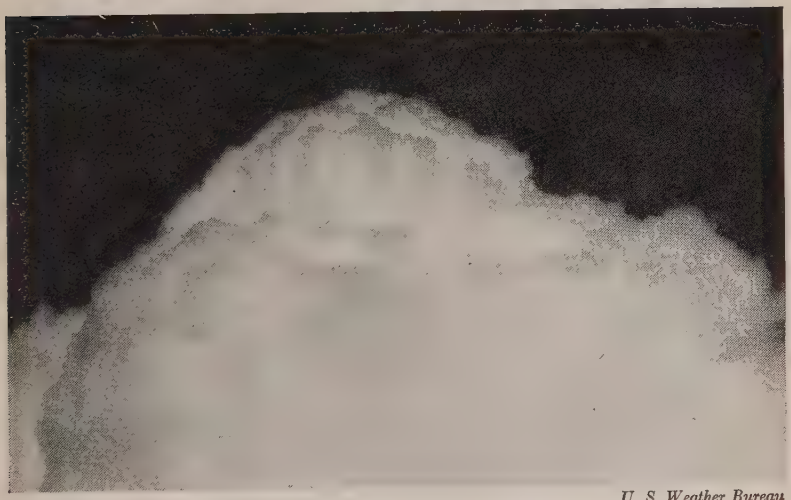
FIG. 293. Cirrus with irregular arrangements of filaments.

U. S. Weather Bureau

FIG. 294. Alto-cumulus, active form.

U. S. Weather Bureau

Fig. 295. Cumulo-nimbus, just grown from nimbus.



U. S. Weather Bureau

Fig. 296. Cumulus congestus.

U. S. Weather Bureau

Fig. 297. Nimbus, with fog or stratus below.

ordinary raindrop, but the friction of the air on the surface of a tiny droplet is so great that the droplet cannot move perceptibly through the air and remains virtually suspended.

The foregoing description of the formation of weather phenomena is of course only a bare introduction to the broad subject of weather, its causes, and its relation to aviation. Yet it is enough, perhaps, to enable us to make a few generalizations and inferences as to what a pilot should do about the weather and its hazards. These are brought together in the next chapter.

Questions

1. What stages does air commonly go through in rising from the earth's surface to a great height?
2. Describe the passing of a warm front.
3. Is it correct to say that, on the approach of a warm front, high, thin clouds from them change to lower, thicker clouds?
4. Describe the passing of a cold front.
5. How are clouds classified as to form? as to composition? as to altitude? as to precipitation?
6. Describe a cumulus cloud; a cirrus cloud; a stratus cloud; a nimbus cloud.
7. Can you explain by geometry why tiny droplets of water can remain suspended in the air?

38

WEATHER — WHAT TO DO ABOUT IT

WE HAVE previously discussed briefly the weather hazards of flying, but these need to be considered in the light of what the pilot should do about them.

Clouds

The danger of flying through clouds without special instruments was discussed at some length in Chapter 29. Clouds as such are not an obstacle to flight, but require the use of the special instruments described in Chapter 39.

What to do about clouds

If you are without instruments and there are clouds ahead, you must not proceed unless you believe you can safely fly under or over them. If you decide to fly over them, you must be able at any time to descend between clouds if necessary.

If you are flying over clouds and they become too close together, descend and fly under them. See Civil Aeronautics Authority regulations, Chapter 43. When flying below clouds, if you find them becoming too close to the ground, either turn back to where the clouds are higher or set the plane down.

Vertical air currents

You have already learned how vertical currents (thermal currents) are caused by heating of the air at the surface. Such vertical currents (one cause of turbulence) can occur on a clear day. In fact it is on a bright sunny day, at

midday or in early afternoon, that turbulence is most likely to occur.

What to do about turbulence

We have already learned that to avoid turbulence (1) fly in the early morning or late afternoon, or (2) fly high, if the turbulence is confined to the lower levels as it often is.

Thin air

By "thin air" is meant air at less than ordinary pressure. It is more difficult for a plane to gain altitude in thin air than in air of ordinary pressure. The principal danger in connection with thin air lies in not allowing sufficient room for the run in a take-off.

What to do about thin air

Just remember that when taking off in thin air you need plenty of length of runway. Remember this especially when you are taking off from an airport in a high altitude, as at Yuma, Albuquerque, or El Paso. Do not think the engine is necessarily at fault if you have to fly all the way around the airport to get a few hundred feet off the ground.

You may even notice the difference in climbing ability of the plane at the same airport, from one time to another as the barometer changes.

If you look at the altimeter each time you take off, to set it at zero, you can tell when the air has become thin. It is thinner than previously when the hand points to an altitude above zero, when previously set at zero on the ground.

Fog

A fog is a cloud resting on the ground. The danger in fog for a pilot is the same as the danger in clouds plus the very great added danger of the pilot's not being able to emerge

from the fog and see the ground in order to land. Moreover, fog obscures obstacles such as poles, towers, and hills, which may be in the way of a plane flying low. The pilot must positively avoid all fog, as a medium in which it is impossible to fly safely.

Fogs form when warm, moist air is cooled below the point of saturation near the ground, as in the case of air blowing from a warm body of water over cooler land, or in the case of surface cooling on a clear night owing to terrestrial radiation causing the temperature to lower to the dew point.

What to do about fog

If you see a fog forming ahead, you will realize that you may not be able to see to land; hence you will turn and fly in a direction free of fog.

If fog begins to form under you and you see no sure direction to fly to escape it, set the plane down at the best available spot while you still can see the ground.

Of course you should try to anticipate the formation of fog. Remember the probability of fog can be anticipated by the difference between temperature and dew point and by the direction and speed of the wind. Watching temperature and dew point is one of the simplest means of forecasting.

Icing

The danger of icing lies principally in the formation of ice on the leading edges of the wings and the propeller in such a way as to affect adversely the aerodynamic shape of the airfoil sections. This icing causes the wings to lose lift and the propeller to lose thrust; the actual weight of the ice itself is of minor importance.

Icing is most likely to occur when the plane is flown through clouds or visible moisture at temperatures near

freezing (between 26° F. and 34° F.). Ice may form because the moisture as it collects on the wings is reduced in temperature by the evaporation caused by the flight of the plane and the moisture freezes.

Icing is very likely to occur in flight through the "warm" air that is sliding up a cold wedge at a warm front. If it is moist air and condensation is occurring because of the lifting of that air, and if the pilot flies through it where the temperature is near freezing, icing conditions probably exist.

Icing below clouds

We have considered icing in clouds. Icing can also occur below clouds, as a result of rain or drizzle falling out of the clouds. The rain or drizzle usually originates at temperatures above freezing; otherwise the precipitation would probably be in the form of snow. It may fall out of a warm layer into a subfreezing layer and be converted into supercooled droplets. These droplets can fall a considerable distance through subfreezing temperatures without freezing. On striking the airplane or the ground they splash and freeze almost instantly. Or with the surface of the plane at subfreezing temperature the rain falling on it will freeze, even though the raindrops themselves are not below freezing temperature. The ice accumulation under conditions of freezing rain can be so rapid as to cause a plane to begin to lose altitude within one minute of exposure to the icing conditions.

Many devices have been tried for keeping ice from forming on wings, or for removing it when formed, but in no case with complete satisfaction.

What to do about icing

If a pilot has reason to believe that icing conditions are present in a cloud layer, he should avoid flying in it if pos-

sible; and if he encounters icing conditions in a cloud, he should try to get out of the cloud.

Freezing rain is the most dangerous of all icing conditions. It should be anticipated if possible and avoided if necessary by not flying. Otherwise, as has been explained, it can be avoided (1) by flying above the freezing level where the precipitation is forming as warm rain; or (2) by flying at a lower level where the temperature is again above freezing and where the ice will not stick to the plane. If any possible icing condition is anticipated a pilot should study the weather in advance, with a view to learning where warm or very cold levels are to be found.

High wind

The danger from high wind lies principally in taxiing after landings, or before take-offs. A plane can fly with perfect safety in a 200-miles-an-hour wind, if it is a steady, uniform wind. Indeed, one hope of those who would fly in the stratosphere is that they will be able to take advantage of high winds.

When a plane is once started down a runway directly into the wind, it can take off or land in a high wind with a very short run on the ground. But if a plane has landed in a high wind, or is taxiing in a high wind preparatory to taking off, the plane is in great danger of being blown over.

There is danger also in a sudden shift of direction of wind, such as may occur in passing through the boundary between warm and cold air at a front. This will result in turbulence and a change in the drift angle.

What to do about a high wind

Never attempt to take off in a high wind unless it is absolutely necessary to do so. Then get plenty of assistants to help hold the plane from being blown over until you taxi into position and give full throttle.

If necessary to land a plane in a high wind, keep it headed directly into the wind, and keep the power on until the plane can be held down by persons on the ground.

There is another danger: a strong head wind may so impede progress that you will be unable to reach an airport before your fuel is used up.

Suppose you have started on a trip, say, east from the airport at 100 miles an hour cruising air speed and find you have a ground speed of 150 miles an hour. You will know that the wind is blowing from the west at 50 miles an hour — or has a westerly component of 50 miles an hour, which amounts to the same thing so far as flying west is concerned; and that, consequently, you can fly back toward the west at only 50 miles an hour. Therefore it will take three times as long to come back from whatever point you may make your turn as it took you to go to that point. Hence, if it is necessary for you to return to the home airport, you can fly east safely under those conditions for only one fourth of the total time that you can safely stay in the air.

Thunderstorms

Thunderstorms occur in deep, dark cumulo-nimbus clouds, and they are always accompanied by violent upward currents in the clouds.

Hail often forms in the thunderclouds. Raindrops freeze, are then carried up by the updrafts, perhaps several times, collecting more moisture and freezing more each time, and thus forming into large hailstones which can demolish a plane.

It has been calculated that the updrafts in a thundercloud may move even as fast as 100 miles an hour on rare occasions, for that speed of rising air is necessary to maintain hailstones until they grow to the size of hen's eggs and larger, as they are sometimes found. At any rate it is

unsafe to fly through a thunderstorm even with updrafts of no more than 30 miles an hour.

What to do about a thunderstorm

From the above description of a thunderstorm it is obvious that in flying you should stay away from all thunderstorms. A thunderstorm is usually a rather local affair. By day it can be seen from a distance, and as a thunderstorm (or any storm) seldom travels more than 30 miles an hour you can easily fly around a thunderstorm of moderate size. Thunderstorms sometimes occur scattered irregularly throughout an air mass as the result of surface heating, and at other times they occur along a summer cold front in a line that may be as long as 400 miles.

If it is not possible to fly around a thunderstorm, find a suitable place to land and set the plane down. Then promptly get it staked down — turn the plane to a position with its tail to the wind and tie the tail wheel and wing struts to stakes or other objects that are firmly attached to the ground. If a front is approaching, consider not only the prevailing wind but also the direction the wind will probably take after the front has passed.

No pilot should set out on any extended trip without stakes and rope. Special light metal stakes are available which hold firmly to the ground.

The plane is turned with its tail to the wind so that the wind will blow the wings down rather than up. If no stakes are available in a high wind, sit on the tail of the plane and hold it down as best you can until the wind dies down.

Line squalls

The term "line squall" is applied to the rapid shift in wind direction which occurs at the edge of a cold front.

A line squall, also, may have violent upward currents dangerous for a plane.

The sudden shift of wind direction at a cold front sometimes presents a hazard in landing. The wind may shift so suddenly that the pilot finds himself trying to land downwind. He may not be able to set the plane down before crashing into a fence or trees or a hangar. Therefore be sure to land and taxi in before the front passes, or stay in the air until after the front has passed.

What to do about a line squall

It is not ordinarily possible to fly around a line squall, because of its extent; therefore, if you know that one is approaching you must turn and fly away from it, or else set the plane down and stake it promptly or otherwise secure it, and wait for the squall to pass. However, if the front has no appreciable weather — clouds or precipitation — in it you may fly through, but watch out for turbulence.

Variable and gusty wind

The term "variable" as applied to wind signifies that the direction of the wind is unstable; that is, the wind is shifting its direction frequently — sometimes suddenly. The term "gusty" signifies that the wind is not uniform in velocity but blows by fits and starts. A wind can be both variable and gusty.

One danger of variable wind is that the plane is likely to be blown suddenly to one side just at the moment of landing, with strain on the landing gear. A serious danger from gusts is that the plane may encounter a decided lull — a marked diminution of wind velocity — when flying or gliding at slow speed in the approach for a landing. In that case the speed of the air with reference to the plane, or the speed of the plane with reference to the air, may be

suddenly reduced; and the loss of flying speed may cause the plane to stall and to strike the ground before it can regain flying speed.

What to do about variable wind and strong gusts

Of course, in view of the above dangers, it is best to be very careful in taking off and landing in variable or gusty wind. The presence of variable wind or strong gusts at an airport is noted in the hourly weather reports of the Civil Aeronautics Administration weather stations. If such winds are reported for the airport at which you are to land, or if you suspect their presence when approaching to land, maintain good flying speed until near the ground, if possible; and be on the alert when the plane is about to touch the ground to have it pointing in the direction in which it is moving over the ground.

Tornado

A tornado is a funnel-shaped storm (see Fig. 298) in which there is a terrific rotation, updraft, and high vacuum. As a tornado passes over a house the house may explode from the pressure of air within, as the pressure of air outside it is suddenly greatly reduced. A tornado need never be a real hazard to a pilot, for it is a very local affair; and though it is terrifically destructive it can easily be seen and avoided altogether, as it does not travel fast horizontally.

What to do about a tornado

Just fly around it — and get a picture of it if you can!

Falling barometer

We have learned how the barometric pressure decreases as a low or a cyclone is approaching. This suggests that if we know that the barometer is falling there is a likelihood

U. S. Weather Bureau

Fig. 298. Photographs of a tornado in central Nebraska. Left, as it had just formed its funnel, or cone, against a background of clouds; center, as it swept along a path less than a thousand feet wide, at a rate of perhaps 50 miles an hour; right, as it struck a farmhouse, which seemed to explode.

that a low or a cyclone is approaching, even though the sky is clear.

What to do about a falling barometer

Remember that an approaching storm is most likely coming from a westerly direction. Don't start on an extended trip, especially in a westerly direction, when the barometer is falling, without a thorough analysis of the weather.

Low barometer

Remember, also, that the sky may be clear and the weather warm while a low is passing. If the barometer reading is low — say 29.5 inches or less — look out for a coming line squall.

High barometer

A high barometer indicates that any bad weather accompanying a low is past for the time being.

What to do about a high

Go ahead and fly!

QUESTIONS

1. What should you do if flying and you see scattered clouds ahead?
2. What should you do if you see a cloud bank ahead?
3. What is the cause of turbulence? How may you avoid flying in turbulent air?
4. What is meant by thin air? Is thin air a source of danger?
5. What is a fog?
6. What is the danger of a fog to a pilot?
7. Explain what to do about fog.
8. What is meant by icing? Is it a danger? Explain.
9. How can icing be avoided?
10. When is high wind a danger? What should be done about it?
11. What danger resides in a thunderstorm? How is it avoided?
12. What is a line squall? Are there dangers connected with a line squall?
13. Are strong gusts dangerous?
14. Is a tornado dangerous? Explain.
15. What does a falling barometer indicate? a rising barometer?

PART V

Aids and Safeguards

Transcontinental and Western Air

FIG. 299. The instrumentation of the T.W.A. Boeing Stratoliner.

39

INSTRUMENT FLYING

WE HAVE already explained that a pilot flying a plane equipped with only the instruments described in Chapter 4 must be able to see the ground or the horizon in order to keep the plane level and to fly straight.

However, there are occasions when a plane must be flown when the pilot cannot see the ground or the horizon, as when flying in a cloud. This is true particularly in the case of airliners and of army planes, which often need to fly in bad weather.

Any plane, therefore, which requires to be flown in clouds or otherwise without visual reference to the ground or horizon must be equipped with special instruments (in addition to those described in Chapter 4) of such kind that the pilot can keep the plane level and can either fly straight or make a given turn by reference to these instruments alone. This kind of flying is called *instrument flying*.

The following are the important additional instruments commonly used for instrument flying:

The *climb indicator* indicates the rate of ascent or descent in altitude.

The *rate-of-turn indicator* (so called, but really a rate-of-yaw indicator) shows the rate of rotation around the normal axis. The turn indicator is usually combined with the bank indicator in a *turn-and-bank indicator*.

The *directional gyro* indicates a compass reading free from errors that occur in the compass as a result of turns, as described later.

The *artificial horizon* (or gyro horizon) shows the tilt of

the horizon with reference to the plane and it also shows whether the horizon would appear above or below the nose of the plane if it could be seen.

The *sensitive altimeter* indicates altitude more precisely than does an ordinary altimeter. A sensitive altimeter is not used in addition to an ordinary altimeter but in place of it.

The climb indicator

The climb indicator, or rate-of-climb indicator, the dial of which is shown in Figure 300, indicates ascent by the upward pointing of the needle and descent by the downward pointing of the needle. The greater the speed of ascent or descent, the farther the needle is from zero.

Principle of the climb indicator

The action of the rate-of-climb indicator is based upon the fact that as we ascend from sea level we find the air exerting less and less pressure.

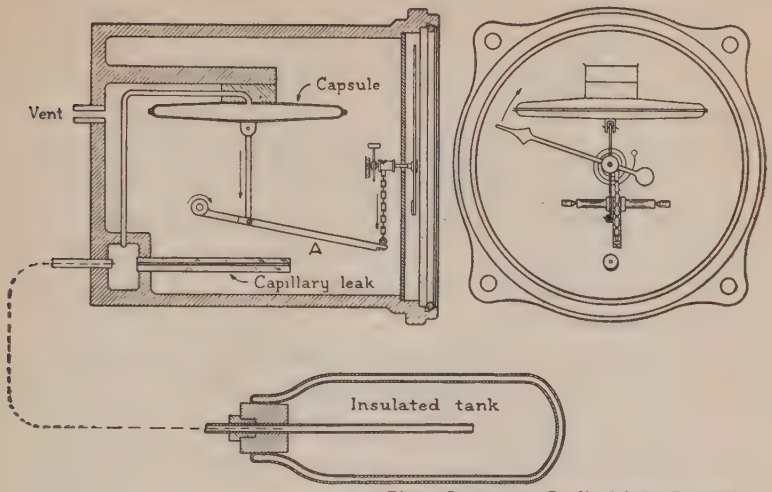
The device measures rate of climb by measuring the difference between the pressure of the air in which the plane is flying and the pressure of the air through which it was flying a few moments earlier.

Figure 301 shows the essential elements of the climb indicator. The instrument contains a metal capsule similar to that used in a barometer, altimeter, or air-speed indicator. There is a vent (opening) in the main chamber which allows outside air to enter freely; so we may think of the capsule as virtually out of doors.

The inside of the capsule is connected by a tube to a thermally insulated tank — like a thermos

Pioneer Instrument. Bendix Aviation Corporation

FIG. 300. A rate-of-climb indicator.



Pioneer Instrument. Bendix Aviation Corporation

FIG. 301. Diagrammatic representation of the mechanism of the rate-of-climb indicator.

bottle — so that the pressure in the capsule will not be greatly affected by changes in temperature.

The air is permitted to enter the capsule and tank through a length of tube with a very small bore. This tube is called a *capillary tube*, or *capillary leak*.

Let us suppose that a plane has been flying at 1000 feet for a while. The pressure is the same inside and outside the capsule. Now suppose that the plane climbs to 1200 feet. The air in the main chamber has the lower pressure normal for 1200 feet, but the air in the capsule and tank has not had time to leak out through the capillary tube and have a pressure as low as that of the air outside the capsule. The pressure inside the capsule and tank is therefore greater than that outside. Hence the capsule expands somewhat.

This expansion pushes down lever *A*; the lever pulls down the chain and turns the dial hand so that it moves up against the hairspring as shown, indicating climb.

Similarly, when the plane is descending, the air in the

main chamber is promptly taking on the increased atmospheric pressure; but the pressure in the capsule and tank are lagging behind because air is being only slowly forced in through the capillary tube. This means that during the descent the pressure in the main chamber is greater than that in the capsule and tank, and the capsule is collapsed somewhat. This causes lever *A* to be raised, the pull on the chain to be released, and the hairspring to pull the dial hand in the opposite direction. The hand then points down, indicating descent.

The greater the rate of ascent or descent, the farther the pressure in the capsule lags behind that of the outer air and the farther the dial hand is rotated from horizontal.

You will realize that there is necessarily a lag in the reading of the rate-of-climb indicator. That is, having flown for a while at 1000 feet, if you suddenly start climbing rapidly it takes a few moments for the difference in pressure between that in the capsule and that outside to reach the maximum for that rate of climb. Theoretically, you could suddenly start to descend while the air in chamber *B* was still of less pressure than that in chamber *A* and while the dial still indicated climb. Only when this difference between pressures becomes constant does the dial hand indicate the true rate of ascent (or descent); that is, only when the pointer is at rest does it indicate the true rate of ascent or descent.

The gyroscope

The rate-of-turn indicator, directional gyro, and artificial horizon, each depends upon the action of a gyroscope.

A gyroscope is essentially a flywheel revolving so rapidly that its momentum of rotation resists change of direction of its axle except in a limited manner.

Figure 302 shows an ordinary toy gyroscope rotating on a horizontal axis with an extension of the frame resting on a

stand. The gyroscope does not drop down immediately because the momentum of revolution resists the effort of gravity to change the direction of the axis of rotation.

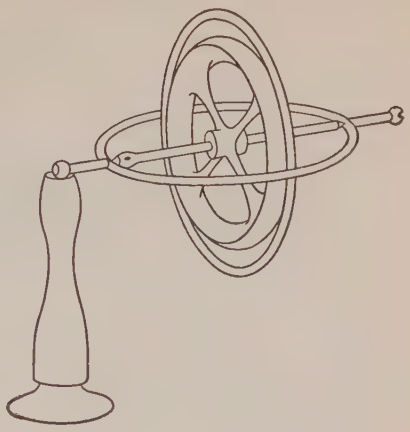


FIG. 302. Toy gyroscope.

Precession

Another important property of a gyroscope is made use of in some instruments. Let us say that a gyroscope is spinning rapidly on a horizontal axle XY extending east and west. Let us say that you are facing north with the rotor (flywheel) spinning away from you at the top, as shown at (*a*) in Figure 303. If you attempt to rotate the axle XY around a vertical axis so as to swing the X end of the axle around to the north and the Y end to the south, as shown in the figure, the gyroscope shows a very strong tendency to assume the position shown at (*b*), with the rotor spinning in the plane of rotation intended for the ends of the axle, X and Y, and in the same direction as that intended for X and Y.

In order to get to position (*b*) from position (*a*), the axle end X must move down and the axle end Y must move up,

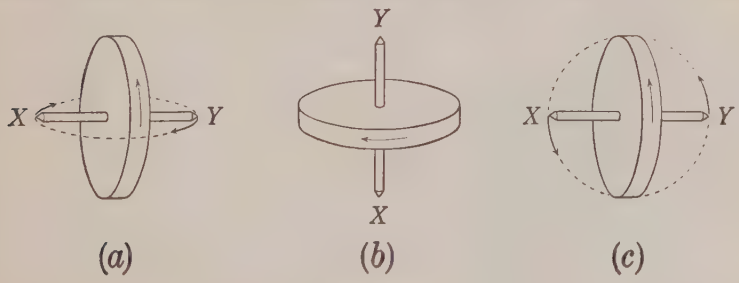


FIG. 303.

as shown at (*c*). This means that any pressure exerted on the axle to rotate it in the direction shown at (*a*) has the effect of rotating the axle in the direction shown at (*c*).

If you try to rotate axle *XY* in the opposite direction, *X* will go up and *Y* down. Or if the rotor at (*a*) is spinning in the opposite direction (over toward you) and you try to rotate axle *XY* clockwise, *X* will go up and *Y* down.

Always the axle tends to move to a position such that the rotor itself spins in the way you tried to get the ends of the axle to rotate. We say that the *axis of spin* tends to align itself with the *axis of rotation*. The axis of spin refers to the axis of the rotor, and the axis of rotation refers to the axis of the rotation that we try to give the axis of spin.

The actual rotation of the spinning axle is at right angles to the direction in which the force is applied to rotate it. This motion at right angles to the force producing it is called *precession*.

Rate-of-turn indicator

This principle of the gyroscope — precession — is used in the rate-of-turn indicator. Let us assume that the axle *XY* of the gyroscope (*a* in Figure 303) is set in pivots in a frame called a *gimbal*, as shown in Figure 304, and that this gimbal

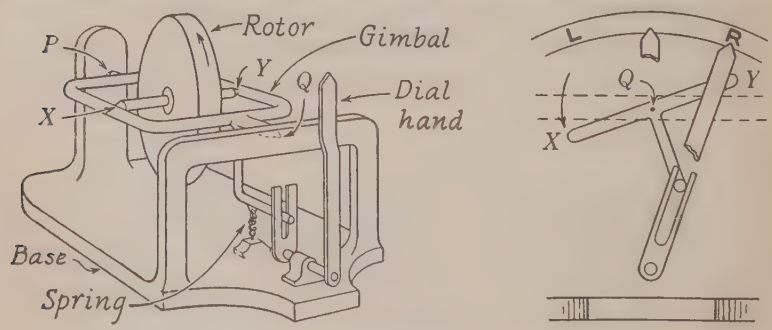


FIG. 304. Diagrammatic representation of the gyroscopic mechanism of the turn indicator.

has pivots P and Q set in arms of the base which is rigidly attached to the plane.

When the plane yaws to the right the gyroscope assembly rotates to the right (clockwise, looking down). But we have seen that any attempt in such a case to rotate axle XY clockwise actually has the effect of making axis XY precess; that is, of causing X to go down and Y to go up. Yawing to the left would lift X and depress Y. In other words, the gimbal rotates on axis PQ, and this rotation is resisted by the spring.

The greater the speed of yaw to the right, the greater the force of precession tending to rotate the gimbal on its axis PQ against the spring, so as to force pivot X to move down.

The rotation of the gimbal is transmitted to the dial hand, as shown, so that the hand points to the right for a yaw to the right and to the left for a yaw to the left; and the greater the yaw, the greater the deflection of the hand from vertical. The rate of yaw is usually indicated in terms of the number of degrees of rotation about the normal axis per minute, regardless of the radius of turn.

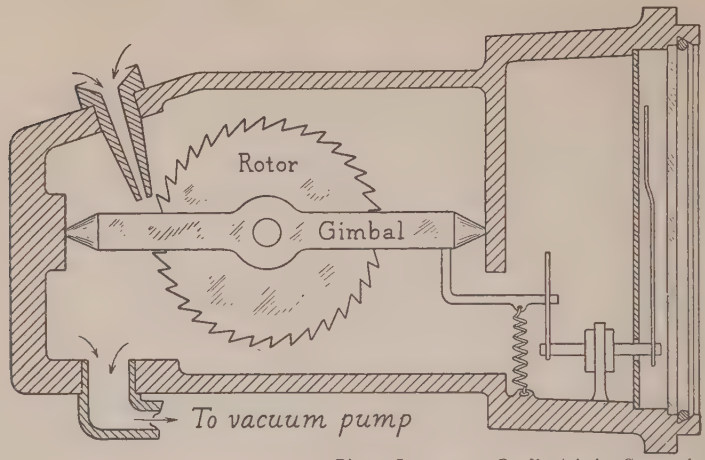
Figure 305 shows the dial of the rate-of-turn indicator which contains also a bank indicator. This combination is called a *turn-and-bank indicator.*

Maintaining rotation of the rotor

The rotor is kept rotating, at perhaps 10,000 revolutions per minute, by a stream of air flowing from a jet toward blades or teeth in the circumference of the rotor, as shown in Figure 306. The air comes from outside the case of the gyroscope, being forced in by normal air pressure as the result of the reduction of air pressure inside the case. This reduction of pressure is

Pioneer Instrument. Bendix Aviation Corporation

FIG. 305. Bank-and-turn indicator.



Pioneer Instrument. Bendix Aviation Corporation

FIG. 306. Diagrammatic cross section of the turn indicator, showing the method of rotating the motor.

produced by an engine-driven vacuum pump, or by a Venturi tube placed in the propeller slip stream.

Inadequacy of the compass

We have already explained how the compass is set so that its needle and card rotate in a damping fluid. This construction is designed to reduce oscillations after a turn; but oscillations cannot be eliminated altogether, and these constitute one shortcoming of the compass. Another and more serious shortcoming of the compass is called the *northerly turning error.*

Northerly turning error

In the northern hemisphere the magnetic lines of force slant downward as well as toward the north. There, if a compass needle were free to turn in any direction, not only would it point north (to magnetic north in the horizontal direction), but also it would point downward, or dip, in a slanting direction. It is as if the needle were trying to

point toward a spot far below the earth's surface under the magnetic pole.

If we could set an ordinary compass upon edge with the *N* still toward the north, as shown in Figure 307, the needle would tend to point down.

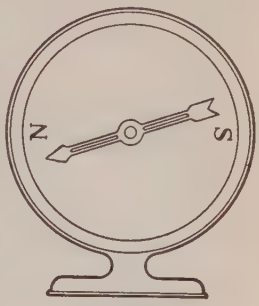


FIG. 307.

When a plane is headed north and is banked for a turn to the left, let us say, the left side of the compass is lowered and the needle in its effort to point downward toward the magnetic pole swings its front end toward the left (the lower side). This means that the compass reading indicates a turn to the *right* — opposite the actual direction of turn. Similarly, if a turn is made from a north heading toward the right with moderate bank, the compass temporarily indicates a turn to the left. When the plane is leveled after the turn and flown straight, the compass oscillates awhile and finally comes to rest indicating the correct reading.

When a turn is made either way from a southerly heading, a similar error occurs. In fact, whenever the plane is banked, except when headed directly east or west, the dipping tendency of the needle causes an erroneous swing. This error is called the *northerly turning error*, regardless of the heading from which the turn may have been made.

It was to avoid the errors of the compass, particularly the consequences of the northerly turning error of the compass, that the *directional gyro* was developed.

The directional gyro

The directional gyro is an instrument used in place of a compass for determining the direction in which a plane is headed. It is like a compass except that, instead of having a needle always pointing north because of the earth's mag-

netic attraction, it has an axis of spin which can be held pointing north by the momentum of a gyroscope rotor.

Figure 308 shows a gyroscope *mounted universally;* that is, mounted by pivots X and Y in a horizontal gimbal ring, R, which in turn is mounted to rotate on a horizontal axis, PQ, in a larger and vertical gimbal ring, G, which in turn is mounted to rotate on a vertical axle, M, in the base of the instrument.

The rotor is kept rotating by a jet of air produced in the same manner as in the case of the rate-of-turn indicator.

The base of the instrument is attached rigidly to the plane. The whole instrument can turn on vertical axle M. Let us say that the Y end of axis XY is pointing forward and that the plane is headed north; hence axis XY points north.

If the plane pitches up or down, axis XY remains level, pointing north; and we may think of gimbal ring G as revolving on axis PQ without affecting the attitude of the rotor in any way.

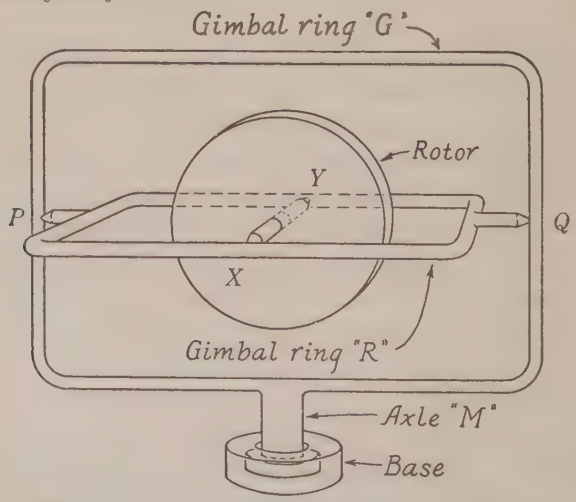


FIG. 308. Diagrammatic representation of the gyroscopic mechanism of the directional gyro.

If the plane rolls to right or left, we may think of the whole of the instrument except the rotor as rotating on axis XY, still leaving axis XY level and pointing north.

If the plane yaws to right or left, we may think of the base as rotating on axle M and leaving the whole instrument above the base undisturbed, with axis XY still pointing north.

You can see, therefore, that if we set the instrument so that axis XY is pointing north when we take off, it continues to point north during the trip regardless of the pitch, roll, or yaw and regardless of the directions in which we may fly. Consequently, if we mount a compass card (scale) on gimbal ring G (Fig. 309), this card serves to show the direction in which the plane is heading exactly like the card in a compass.

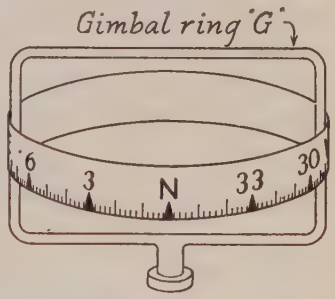


Fig. 309. How the compass card is mounted on a gimbal of the directional gyro.

The scale or card is seen through a window having a lubber line like a compass, and it is used as a compass. The instrument requires to be adjusted from time to time in steady, straight flight by reference to a magnetic compass, this to correct the reading for any slight error arising from precession due to friction.

The advantages of the directional gyro over the magnetic compass are that it is not subject to the northerly turning error and that it does not oscillate. It is especially valuable, therefore, in the making of turns.

Turn indicator and directional gyro compared

You will see that both the turn indicator and the directional gyro have to do with measurement of yaw. The directional gyro indicates the total amount of yaw, while

the turn indicator measures the speed of yaw. The directional gyro is based on the capacity of the gyro rotor to hold its direction of rotation while the airplane yaws, rolls, and pitches. The turn indicator is based on the tendency to precess when the axis of rotation of the gyro is forcibly turned. In the one case we use the directional inertia of the gyro (tendency of its axis to point in a fixed direction in space) and in the other we use the force of precession, a characteristic which exists only in a gyroscope.

The artificial horizon

The artificial horizon, or gyro horizon, also makes use of the directional inertia of the gyro. The operation of the artificial horizon indicator is illustrated in part, diagrammatically only, by Figures 310 to 314.

Figure 310 shows a gyroscope with rotor R mounted with its axis XY vertical and pivoted in vertical gimbal frame G,

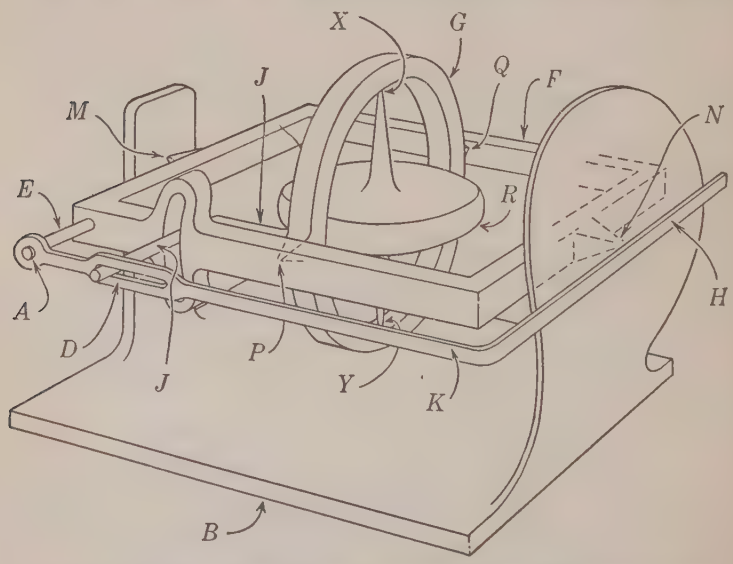


FIG. 310. The gyroscopic mechanism of the artificial horizon.

which in turn is mounted on horizontal gimbal frame F by the pivots P and Q.

Gimbal frame F is mounted with a horizontal axis MN on the base, which is attached rigidly to the plane. Axis MN is parallel to the longitudinal axis of the plane, M being the front end.

Rotor R is spun very rapidly, say 12,000 revolutions per minute, by a stream of air drawn into the rotor chamber by suction, as in the case of the rate-of-turn indicator. Axis XY tends to remain vertical unless forcibly tilted. A special arrangement of *pendulous vanes* (not shown) assists the rotor axle to remain vertical; that is, vertical with reference to the earth, not with reference to the plane (Fig. 311).

With axis XY always vertical, axis PQ is kept always horizontal — parallel with the horizon. Hence bar E, which is an extension of frame F, is always horizontal. Bar H is always parallel to bar E, and hence it, too, is always horizontal. Bar H is visible in the window of the artificial horizon (instrument) and indicates the horizon.

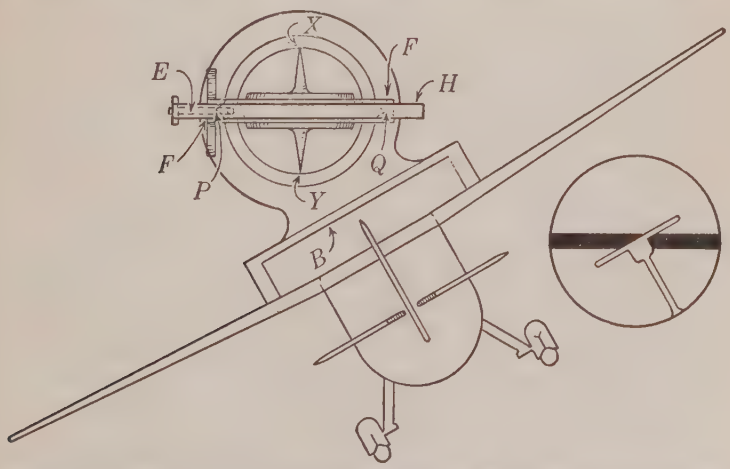


FIG. 311. The means by which the artificial horizon of the plane indicates a banked position.

When the plane is banked as shown in Figure 311, although the base of the instrument is inclined at the angle of bank, axis *MN* remains level and the position of the whole gyroscope between pivots *M* and *N* is the same as when the plane is level. That is, horizon bar *H* is horizontal and appears in the window of the plane, as shown in the round inset in Figure 311.

A miniature plane is mounted in the front of the window of the instrument, with its wings always parallel to the wings of the plane itself, as shown in the inset in Figure 311.

When viewed from the tilted position in which the pilot may be sitting, the miniature plane seems horizontal and the horizon seems tilted, as the horizon itself would appear to the pilot (*B* in Figure 312). When the plane is banked

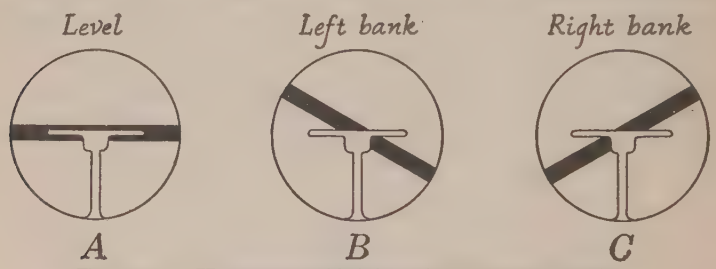


FIG. 312. How the artificial horizon shows banking.

to the right (opposite to the banking shown in Figure 311) the "horizon" (*H*) in the instrument seems to tilt as shown at *C* in Figure 312.

When the plane pitches downward, as shown in the upper round inset in Figure 313, the gyroscope frame, or base, also pitches downward, as shown in Figure 313. But the rotor *R* is always horizontal, axis *XY* is always vertical, and axis *PQ* is always horizontal; hence extension *J* on gimbal *G* is always horizontal and hinge *D* is always on a level with axis *PQ* (Fig. 310). But as the plane pitches down and axis *MN* pitches down, hinge *A* is lower than axis *PQ*; hence rod *K* extends slantingly upward from hinge *A* toward the

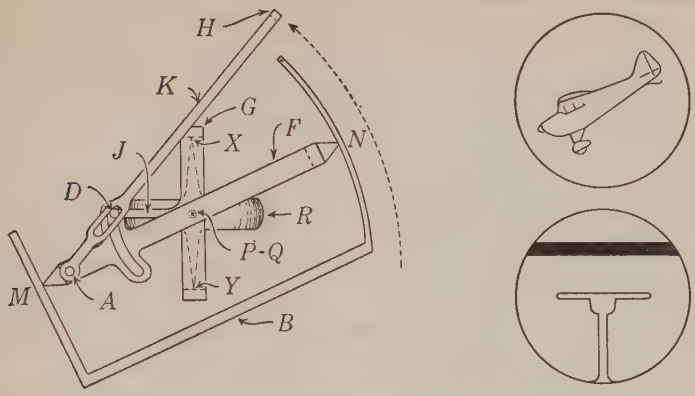


FIG. 313. The means by which the artificial horizon indicates a pitched position of the plane.

rear of the plane more steeply than axis MN, and (horizon) bar H is raised as shown (exaggerated) in Figure 313.

With a moderate pitch downward bar H will still show in the window of the instrument, as in the lower round inset in Figure 313. It appears higher than normal in a downward pitch, like the actual horizon.

If the plane pitches up, the horizon bar goes down with reference to the window, and the window appears as at C in Figure 314. When banking and pitching are combined, the window appears as shown at D, E, F, and G.

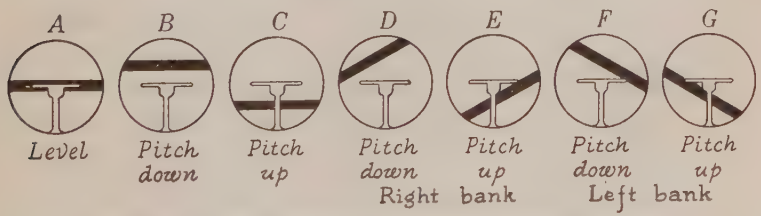


FIG. 314. How the artificial horizon shows pitching.

Automatic pilot

A plane is designed to be stable in flight; that is, to return to level flight after being disturbed by air currents, by

virtue of characteristics of design that were explained in Chapter 13. But it often happens that the attitude of a plane will be so disturbed by strong gusts as to be slow in righting itself, and in order to right the plane promptly the pilot must use the controls.

The artificial horizon indicator and directional gyro have been combined into an automatic pilot. This is a mechanism for controlling the ailerons, elevators, and rudder of the plane, to restore it more promptly to level flight than it can be restored by the automatic stability characteristics that have been mentioned.

The automatic pilot also does more than the stabilizing characteristics of a plane can do. For example, if a gust of air yaws the plane appreciably, the plane does not automatically come back to the same heading — it is just as stable heading in one direction as in another when it is not skidding or slipping. The automatic pilot when set for the desired course returns the plane to that course if it is veered off by any agency.

Sensitive altimeter

Some planes are equipped with a special type of altimeter called a *sensitive altimeter* that is graduated to 20-foot intervals. A sensitive altimeter has two hands like a clock. When pointed to by the long hand the numbers 1, 2, 3, etc., on the dial indicate 100 feet, 200 feet, 300 feet, etc.; and when pointed to by the shorter hand indicate 1000 feet, 2000 feet, 3000 feet, etc. A sensitive altimeter may have a third hand, still smaller, as in Figure 315, to indicate tens of thousands of feet. The dial in this figure indicates about 617 feet.

The altimeter depends upon differences in pressure to measure altitude, and it follows that if the pressure at sea level changes, the altimeter reading at sea level will change.

If the altimeter is set one day to read zero at sea level and the pressure decreases over night, the next day the altimeter will show a reading above zero at sea level; if the pressure has increased, the altimeter will show a reading below zero.

A pilot may set his altimeter to read zero at sea level at the beginning of a flight, and at the end of the flight (say at another airport) it may happen that the air pressure is different; hence the altimeter no longer reads zero at sea level.

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FIG. 315. The sensitive altimeter.

The pilot before landing may wish to set the altimeter to show zero at sea level at the time and place of landing, so that the altimeter will indicate the true altitude of the airport as the wheels touch the ground. In order to do this, the pilot must know the pressure of the air (the barometer reading) at the airport that he is approaching. This information is furnished the pilot from time to time by radio from various airports — those stations having radio ranges. Thus at the conclusion of a weather report for the airport the announcer will say, "Altimeter setting so-and-so" — let us say 29–92. That means the barometer reading is 29.92 inches. In that case the pilot sets his altimeter, by means of the thumbscrew, so that the pointer points to 29.92 on the scale in the window at the right, as shown in Figure 315. The altimeter then gives correct altitude readings for that station at that time.

In the ordinary altimeter the position of the pointer is fixed for a given pressure and the thumbscrew rotates the scale. In the sensitive altimeter the scale is fixed and the thumbscrew adjusts the hands in accordance with the pressure.

Questions

1. What is meant by instrument flying?
2. Why is a compass inaccurate in measuring a turn?
3. Why does a pilot have difficulty in keeping a plane level if he is flying in a fog?
4. What principal instruments are used in instrument flying that are not used in contact flying?
5. What is a capillary tube? In what instrument is it used?
6. Explain the principles on which a climb indicator works.
7. What is a gyroscope?
8. What are some of the important characteristics of a gyroscope that make it useful in avigational instruments?
9. What is precession?
10. What is a gimbal?
11. What is a rotor? What keeps a rotor turning?
12. Explain the principles on which a rate-of-turn indicator works.
13. What is meant by northerly turning error?
14. What is a directional gyro? How does it work?
15. What is the difference between a turn indicator and a directional gyro?
16. What is an artificial horizon?
17. Does an artificial horizon indicate yaw? pitch? bank? Explain.
18. What is an automatic pilot?
19. What is a sensitive altimeter?
20. How does a sensitive altimeter indicate altitude more sensitively than an ordinary altimeter?
21. What setting is required in a sensitive altimeter?

40

WEATHER REPORTING

THE Civil Aeronautics Authority was created by an act of Congress in 1938 to aid and safeguard flying. Effective June 30, 1940, the Civil Aeronautics Authority was divided into two parts — one under the Civil Aeronautics Board, which may be thought of as the legislative branch of the Civil Aeronautics Authority, and the other under the Administration of Civil Aeronautics, which may be thought of as the executive branch of the Civil Aeronautics Authority. The Authority has main offices at Washington, D. C., and branch offices at the principal airports.

Functions of the Civil Aeronautics Authority

The Civil Aeronautics Authority formulates and issues rules and regulations pertaining to every phase of flying. The following are among its functions:

(1) To gather and disseminate information about the weather;

(2) to examine pilots and prospective pilots for knowledge and skill in flying, and to certificate them;

(3) to examine airplanes as to airworthiness and to certificate them for use;

(4) to formulate and enforce rules and regulations pertaining to air traffic.

Weather reporting

Airlines provide their own weather-analyzing service, but for the benefit of private pilots and others the Civil Aero-

nautics Authority has set up a system of *aerological stations* most of which are located at or near a principal airport.

Hourly weather reports

Each aerological station observes the weather hourly and transmits a report hourly to the other stations in the general locality by teletype (a special electric typewriter). In this way each station knows the state of the weather at surrounding stations. A special report is issued by a station at any time when the weather information changes in an important way at that station.

Sequence reports

Each station receives on the teletype a group of reports coming from the various stations in the region. This group of reports is called a *sequence report.*

The principal information given in a sequence report regarding each station is as follows:

A. Sky–weather–visibility:

1. Height of cloud base (called a *ceiling* if clouds cover more than half the sky).
2. Sky condition (as to degree of cloudiness).
3. Visibility in miles (stated if less than 10 miles).
4. Weather conditions (such as rain or snow).
5. Obstructions to visibility if any (such as smoke, haze, or dust).

B. Pressure–temperature–wind:

1. Barometric pressure in millibars, corrected to sea level.
2. Air temperature.
3. Dew point.
4. Wind direction, speed, and character.
5. Altimeter setting (barometric pressure in inches).

Radio weather reports

A radio communication station employee at most directional radio range stations announces hourly selected sequences received at his station. That is, he gives the weather at his station and at various stations reporting to his station. This is done on the radio range frequency, which is not receivable by an ordinary home radio. Radios on planes can receive these announcements. Portable radios having an aviation band of frequencies may be purchased; they enable a pilot (or anyone) to obtain these weather reports hourly.

Symbol weather reports

The reports received on the teletype are greatly abbreviated by the use of symbols and abbreviations. It is very desirable for the pilot to know these, so that he can read the teletype reports posted in the weather bureau office, or coming in on the teletype, not having to ask for a translation.

Table 17 presents some winter sequence weather reports as they appeared on the teletype. The meaning of these sequences is shown in Tables 18 and 19.

The Washington report (line 1 of Table 17) is read as follows:

Washington — contact; ceiling unlimited; scattered clouds at 4000 feet; visibility, 10 miles or more; barometric pressure, 1013.9 millibars; temperature, 28°; dew point, 15°; wind, west, 27 miles an hour, strong gusts; altimeter setting, 29.93 inches.

In giving sequence weather reports over the radio it is customary to repeat the name of the station and its accompanying classification because pilots often have difficulty in hearing the broadcasts. It is customary also to omit the barometric pressure in millibars, since this is for weather-map makers and is not needed by pilots.

TABLE 17

1735 E
WA C 40⦶ 139/28/15→27+/993
BO C E40⦷ 135/27/3→↘30+/992
WAB E20⊕ 135/23/−2↘18−/992
PG C E30⦷8SW− 115/22/8↘16/986
XA SPL 40⦷4BS−F− 078/8/2→↗19+/966
LG C E35⊕⦷5SW−H 108/15/4→↗20−/981
TL N E20⦷11/4VGS− 251/10/6→↘22+/019
ML 25⦶8 12/7↘21
CG C −⊕/⦶217/39/15↓↘13/016
WR ◯ 26/5↘20+
WM SPL 2⊕−⦷1R−F− 112/45/44↓↘5/985
ZN C −⦶/ 200/59/42↓11−/012/RANOT BRONO ZONOT

AG X SPL 1745C 2V⊕11/2VL−F− 105/43/42←↙9/984
LG N SPL 1755E 7⊕11/4VS− 227/32/M←18/019
CC N SPL 1810E 23V⊕12⦶2K−F− 041/43/43↗5/964
L− ENDED 1725E CIG RGD

The time of day at which the sequence report is issued appears at the top of the report, as shown in Table 17 (1735E means 5 : 35 P.M. Eastern Standard Time), and each line of symbols following is the symbol weather report of a station.

In general a symbol weather report contains the following groups of symbols:

(1) Letters (usually two) designating the station to which the report pertains.

(2) Classification of the weather (C, N, or X — explained below) if the station is at a control airport.

(3) Symbols relating to sky–weather–visibility. (See Table 18.)

(4) Symbols relating to pressure–temperature–wind.

(5) Remarks, such as statements of important changes in weather that have occurred since the last report.

A report is indicated as special (SPL) when crucial changes have occurred in weather conditions since the last report; and if the report is not a regular hourly report, the time of issue is given as shown following the letters SPL in the last three reports of Table 17.

Translating a symbol weather report

In order to read the symbol weather reports on the teletype, you will need to know the meanings of the various symbols and abbreviations. These are given in Table 19.

It is helpful to note that the symbols of the sky–weather–visibility group are run together without spacing, but are separated from the other symbols by spaces. This group is easily identified by the circles representing the nature of the clouds. Note also that the symbols of the pressure–temperature–wind group are also run together without spaces. This group is easily identified by the wind-direction arrows and the slanting lines (usually three) which separate the items within the group. Remember that 3-figure numbers give pressure, and 1-figure or 2-figure numbers separated by a slanting line are the temperature and dew point.

In the Washington report of Table 18 the 40 indicates that the cloud base is at an altitude of 4000 feet. But since the clouds are "scattered" — that is, covering less than one half of the sky — they are not considered as constituting a ceiling, as explained in Table 19; and the radio announcer giving this sequence report, if he mentioned the ceiling, would say, "Ceiling unlimited."

Note that in some instances no classification is given, as in the case of Allentown. A classification is given only in the case of a controlled airport.

Of course when the sky is "clear," as indicated by ○, no altitude of cloud base is given, there being no cloud base.

TABLE 18. MEANINGS OF THE SEQUENCE REPORTS GIVEN IN TABLE 17.

STATION	CLASSIFICATION	ALTITUDE OF CLOUD BASE (FEET)	CLOUDS	VISIBILITY	WEATHER CONDITIONS OBSTRUCTIONS TO VISION	PRESSURE (MB.)	TEMP.	DEW POINT	WIND			ALTIMETER SETTING
									Direction	*M.P.H.*	*Gusts*	
Washington	Cont.	* 4000	Scattered	(10 +)		1013.9	28°	15°	W	27	strong	29.93
Baltimore	Cont.	Est. 4000	Broken	(10 +)		1013.5	27°	3°	W–NW	30	strong	29.92
Aberdeen		Est. 2000	Overcast	(10 +)		1013.5	23°	−2°	NW	18	fresh	29.92
Philadelphia	Cont.	Est. 3000	Broken	8	Light snow; showers	1011.5	22°	8°	NW	16		29.86
Allentown (Special)		4000	Broken	4	Light blowing snow; light fog	1007.8	8°	2°	W-SW	19	strong	29.66
La Guardia	Cont.	Est. 3500	Overcast; lower broken	5	Light snow showers; haze	1010.8	15°	4°	W–SW	20	fresh	29.81
Toledo	Inst.	Est. 2000	Broken	$1\frac{1}{4}$ var.	Light drifting snow	1025.1	10°	6°	W–NW	22	strong	30.19
McCool		* 2500	Scattered	8			12°	7°	NW	21		
Chicago	Cont.	* 10,000 +	High thin overcast; lower scattered	(10 +)		1021.7	39°	15°	N–NW	13		30.16

Warsaw			Clear	(10 +)			26°	5°	NW	20	strong	
Mitchel (Special)		200	Overcast; lower thin broken	1	Light rain; light fog	1011.2	45°	44°	N–NW	5		29.85
San Antonio	Cont.	* 10,000 +	High thin scattered	(10 +)		1020.0	59°	42°	N	11	fresh	30.12
(Range not operating — broadcast not operating — zone marker not operating)												
Atlanta Spec. 5 : 15 P.M. C.S.T.	Closed	200 variable	Overcast	$1\frac{1}{2}$ var.	Light drizzle; light fog	1010.5	43°	42°	E–NE	9		29.84
La Guardia Spec. 5 : 55 P.M. E.S.T.	Inst.	700	Overcast	$1\frac{1}{4}$ var.	Light snow	1022.7	32°	Miss-ing	E	18		30.19
Cincinnati Spec. 6 : 10 P.M. E.S.T.	Inst.	2300 variable	Overcast; scattered at 1200	2	Light smoke; light fog (Light drizzle ended 5 : 25 P.M. E.S.T. Ceiling ragged)	1004.1	43°	43°	SW	5		29.64

* Ceiling unlimited.

TABLE 19

Symbols and Abbreviations Used in Symbol Weather Reports

Time of report (based on 24-hour clock)

015 E	12 : 15 A.M.	Eastern Standard Time
430 E	4 : 30 A.M.	Eastern Standard Time
845 C	8 : 45 A.M.	Central Standard Time
1200 C	12 : 00 noon	Central Standard Time
1315 M	1 : 15 P.M.	Mountain Standard Time
1630 M	4 : 30 P.M.	Mountain Standard Time
2045 P	8 : 45 P.M.	Pacific Standard Time
2400 P	12 : 00 midnight	Pacific Standard Time

Station designator (identification)

The identification letters of some of the principal stations are as follows:

AB	Albuquerque,	N. M.	KC	Kansas City,	Mo.
AG	Atlanta,	Ga.	LG	New York, (La Guardia Field)	N. Y.
AQ	Amarillo,	Tex.			
AZ	Albany,	N. Y.	LS	St. Louis,	Mo.
BJ	Buffalo,	N. Y.	MM	Miami,	Fla.
BO	Baltimore,	Md.	MP	Minneapolis,	Minn.
BU	Burbank, (Los Angeles)	Cal.	PS	Memphis,	Tenn.
			NA	Nashville,	Tenn.
BW	Boston,	Mass.	NK	Newark,	N. J.
CC	Cincinnati,	O.	NO	New Orleans,	La.
CG	Chicago,	Ill.	OA	Oakland,	Cal.
CV	Cleveland,	O.	PG	Philadelphia,	Pa.
CX	Cheyenne,	Wyo.	PO	Portland,	Ore.
DT	Detroit,	Mich.	PT	Pittsburgh,	Pa.
EO	El Paso,	Tex.	RW	Richmond,	Va.
FV	Fort Worth,	Tex.	SL	Salt Lake City,	Utah
HX	Harrisburg,	Pa.	TN	Trenton,	N. J.
JK	Jacksonville,	Fla.	WA	Washington,	D. C.

Classification of weather

C = contact; satisfactory for contact flight

N = instrument; requiring observance of instrument flight rules

X = closed; take-offs and landings suspended for all non-scheduled civil aircraft

TABLE 19 (*Continued*)

Cloud base

0 = less than 51 feet
6 = 600 feet
35 = 3500 feet
E35 = estimated 3500 feet
35V = 3500 (variable)
No symbol = 10,000 feet or over
+ 35 = more than 3500 feet — observation balloon blown away

The height of the cloud base is called the *ceiling* when the clouds are *broken* or *overcast*. If the sky is clear, or the clouds are *scattered*, or the altitude of the broken clouds or overcast is 10,000 feet or more, the ceiling is said to be unlimited.

Sky condition

No symbol = sky unobservable
○ = clear
◐ = scattered clouds
◍ = broken clouds
⊕ = overcast
/ = high — over 10,000 feet; thus ◍/ = high broken
⊕/◐ = high overcast — lower scattered
⊕/◍ = high overcast — lower broken
+ preceding symbol = dark; thus +◍ = dark broken
− preceding symbol = thin; thus −◐ = thin scattered
◍/35◐ = high broken — lower scattered at 3500 feet

Visibility

No figure = 10 miles or more
3 = 3 miles
2V = 2 miles — variable
1/2 = $\frac{1}{2}$ mile
11/4 = $1\frac{1}{4}$ mile

Weather conditions

R = rain
ZR = freezing rain
S = snow
L = drizzle
ZL = freezing drizzle
E = sleet
A = hail
AP = small hail
SP = snow pellets
SQ = snow squall
RQ = rain squall
T = thunderstorm
SW = snow showers
RW = rain showers
TORNADO = tornado!
− = light; thus S− = light snow
+ = heavy; thus R+ = heavy rain

TABLE 19 (*Continued*)

Obstructions to vision

F = fog	BS = blowing snow
GF = ground fog	GS = drifting snow
IF = ice fog	BD = blowing dust
H = haze	BN = blowing sand
K = smoke	− = light; thus K− = light smoke
D = dust	+ = heavy or thick

Barometric pressure

096 = 1009.6 millibars (1000 and decimal point omitted)
125 = 1012.5 millibars
987 = 998.7 millibars (900 and decimal point omitted)

Temperature and dew point

59 = 59° F.
0 = 0° F.
− 10 = − 10° F.
72/68 = temperature 72° F., dew point 68° F.

Wind direction and speed, and wind shifts

C = calm
↓ = north (from the north)
← = east
↑8 = south, 8 miles an hour
→20E = west, estimated 20 miles an hour
↙ = NE
↖ = SE
↗− = SW — fresh gusts
↘+ = NW — strong gusts
↓↙ = north-northeast — halfway between the two
↑↗ = south-southwest; etc.
↑12←1745+ = south, 12 miles an hour, shifted from east severely at 5 : 45 P.M.
↑12←1845− = south, 12 miles an hour, shifted from east mildly at 6 : 45 P.M.

Altimeter setting

998 = 29.98 inches
000 = 30.00 inches
012 = 30.12 inches

Winds aloft

Among other items of information about the weather given by the aerological stations is the velocity (speed and direction) of the wind at various levels. For example, at the surface of the ground the wind may be blowing from the south (180°) at 12 miles an hour; at 2000 feet the wind may be blowing from 190° (10° west of south) at 16 miles an hour; at 4000 feet the wind may be blowing from 200° at 24 miles an hour; at 6000 feet the wind may be blowing from 270° (west) at 40 miles an hour; and so on.

This information is spoken of as the "winds aloft." It is valuable to a pilot because it enables him to choose an altitude that will give him the best tail wind, or to avoid a strong head wind.

Observing winds aloft

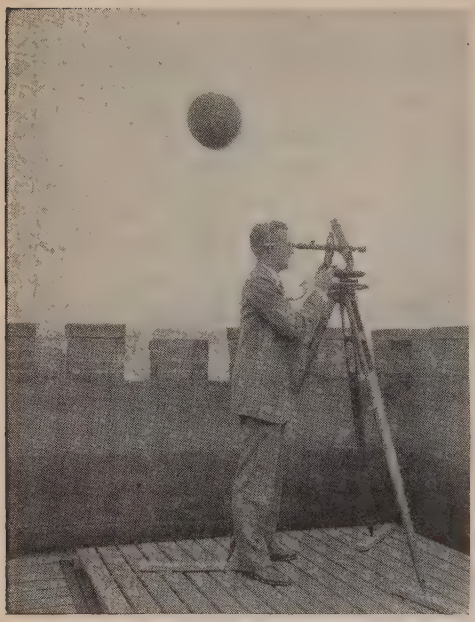
The direction and speed of winds aloft are obtained periodically at various airports by the use of *balloons*. The meteorologist inflates a rubber balloon with *helium* to a diameter of about 2 feet. It is then weighed to make sure it has the right lift and hence will have the right rate of ascent. The balloon is taken out of doors and released. It is watched through a telescopic instrument called a *theodolite* (Fig. 316), and at the end of each minute the direction and elevation angles are read and recorded. A balloon may be watched sometimes for 30 minutes or longer before it enters a cloud or vanishes in the distance.

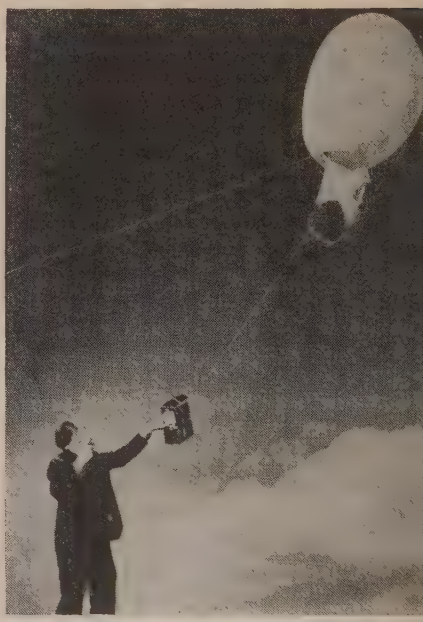
The data thus obtained are plotted, and from the plotted points it is possible to determine the direction and velocity of the wind during each minute and hence at each altitude.

The reporting of winds aloft

The velocities of winds at various altitudes above sea level are reported on the teletype as follows:

LG14 01209 1316 21420 1525 41733





FIGS. 316 and 317. A theodolite in use (left), and a radiometeorograph being launched (right). A sounding balloon carries the radiometeorograph to high altitudes, and the parachute attached retards the fall of the radiosonde after the balloon bursts. The radiosonde sends back signals which indicate temperature, air pressure, and humidity at all heights reached by the balloon.

The meaning of this report is as follows:

LG	14	= La Guardia Field, N. Y., 14 o'clock (2 P.M.)
0	12 09	= 0 thousand feet, wind from 120° at 9 miles an hour
	13 16	= 1 thousand feet, wind from 130° at 16 miles an hour
2	14 20	= 2 thousand feet, wind from 140° at 20 miles an hour
	15 25	= 3 thousand feet, wind from 150° at 25 miles an hour
4	17 33	= 4 thousand feet, wind from 170° at 33 miles an hour

Reports of winds aloft may extend to winds much higher than 4000 feet. Note that in the report the altitude is indicated only for even numbers of thousands of feet, and that only the first two digits of the wind-direction angle are given.

PROBLEM 1. Which would be the more helpful to a pilot flying due south with 80 miles an hour air speed,

(1) a 20-mile wind from the north or
(2) a 30-mile wind from the northeast?

We know that the 20-mile wind from the north would give the plane in this case a speed of 80 plus 20 or 100 miles an hour, with reference to the ground. The problem is to find the ground speed possible with the help of the 30-mile wind from the northeast, and compare this with 100 miles an hour.

SOLUTION.

1. Draw *MN* (Fig. 318) to represent north. *NM* represents the direction in which it is desired to fly.

2. Draw any line *PO* in the direction 225° as shown and lay off *PQ* 30 units long to represent the velocity of the wind for one hour.

3. With *Q* as center and a radius of 80 units, draw an arc cutting *MN* at *R*. *QR* therefore shows the heading of the plane and the distance it moves in an hour with respect to the air.

As we learned in Chapter 23, vector *PR* shows the distance the plane will actually move with reference to the ground in one hour with the help of the 30-mile northeast wind. Measuring *PR*, we find it to be slightly less than 100 units (between 97 and 98), showing that if we are flying due south at 80 miles an hour, air speed, a northeast wind at 30 miles an hour would give us a speed of between 97 and 98 miles an hour with reference to the ground. This, then, would be slightly less helpful than a 20-mile wind blowing directly from the north.

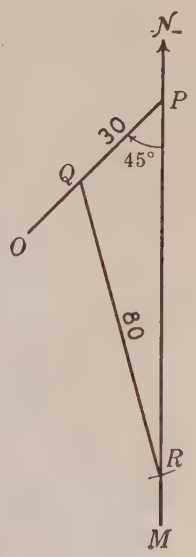


FIG. 318.

There is no difference, of course, between this problem and a problem of finding the heading necessary to make good a given course, such as you had in Chapter 23 on Wind drift, except that in this problem only the ground speed is needed in order to make the comparison.

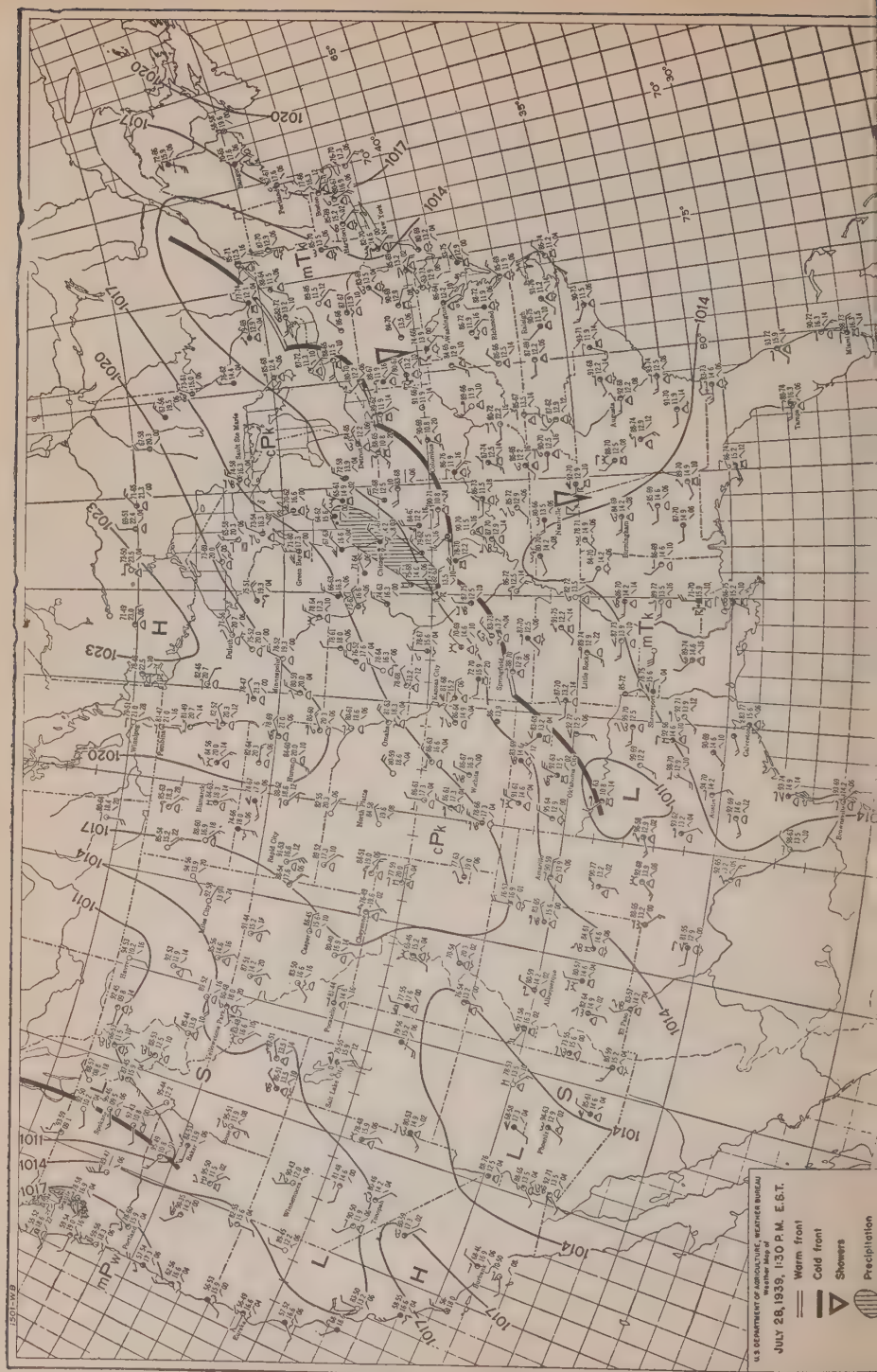


FIG. 319. A weather map.

Weather maps

Many aerological stations draw one or more weather maps each day from data supplied by other stations. Such a weather map is shown in Figure 319.

You already know how to interpret the isobars and fronts. (Note the series of "stable waves" on this map.) You need to understand the symbols representing sky conditions and wind velocity. These are indicated for each station by a symbol consisting of a circle with a tail, as shown in Figure 320.

The amount of shading of the circle shows roughly the portion of sky covered by clouds. The tail shows the approximate direction from which the wind is blowing, and the number of half barbs on the tail indicates the velocity of the wind in accordance with a scale known as the Beaufort Scale, as given in Table 20. In Figure 320, $3\frac{1}{2}$ barbs = 7 half barbs = Beaufort number 7.

Fig. 320.

Exercise 1. What time is indicated by the following symbols?

(*a*) 1432E (*b*) 1642C
(*c*) 1850M (*d*) 2030P

Exercise 2. Translate the sequence weather reports of Table 17.

Exercise 3. Visit a weather communications office at an airport and read the teletype symbol weather reports on file.

Exercise 4. Translate these reports of winds aloft:

(*a*) DT08 02008 2110 22212 2416 42620
(*b*) JK10 03010 3214 23418 0320 40526 1440
(*c*) OA16 00000 3309 23016 2730 42440 2043 62132

Exercise 5. Which would be more helpful to a plane flying northward, a south wind at 20 miles an hour or a wind from 125° at 35 miles an hour? (Air speed, 100 miles an hour.)

TABLE 20

Beaufort Scale for Estimating and Expressing Wind Velocities

BEAUFORT NUMBER	SPECIFICATIONS FOR USE ON LAND	MILES PER HOUR	TERMS USED IN U. S. WEATHER BUREAU FORECASTS [1]	BARBS ON SYMBOL
0	Calm; smoke rises vertically.	Less than 1		(none)
1	Direction of wind shown by smoke drift, but not by wind vanes.	1–3	Light	/
2	Wind felt on face; leaves rustle; ordinary vane moved by wind.	4–7		/
3	Leaves and small twigs in constant motion; wind extends light flag.	8–12	Gentle	//
4	Raises dust and loose paper; small branches are moved.	13–18	Moderate	//
5	Small trees in leaf begin to sway; crested wavelets form on inland waters.	19–24	Fresh	///
6	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	25–31	Strong	///
7	Whole trees in motion; inconvenience felt in walking against wind.	32–38		///
8	Breaks twigs off trees; generally impedes progress.	39–46	Gale	////
9	Slight structural damage occurs (chimney pots and slate removed).	47–54		////
10	Seldom experienced inland; trees uprooted; considerable structural damage occurs.	55–63	Whole gale	/////
11	Very rarely experienced; accompanied by widespread damage.	64–75		/////
12		Above 75	Hurricane	//////

[1] Except for the word "calm," these terms are not ordinarily used in aeronautical weather reports and forecasts.

Questions

1. The Civil Aeronautics Authority is divided into what two parts?
2. Can you name four principal functions of the Authority?
3. In what way is the weather at various localities made known to pilots?
4. What items of information about the weather are given in the sequence reports?
5. What do N, C, and X denote when referring to the weather at an airport?
6. What time is represented by 2045E?
7. What does each of these symbols mean? ○, ⊖, ⦶, ⊕
8. What do these abbreviations mean in a sequence report? R, S, L, E, A, T, F, H, K, D.
9. What barometric pressure in millibars is represented by 096? 987?
10. What description of wind effect is given in the Beaufort scale for wind of 8–12 miles an hour? 13–18? 19–24? 25–31? 22–38?

41

PILOT CERTIFICATION

THE certification of pilots is explained in Civil Aeronautics Bulletin No. 22, entitled "Digest of Civil Air Regulations for Pilots," which may be obtained for 20 cents from the Superintendent of Documents, Washington, D. C.

As stated in the above bulletin, "it is unlawful for any person to serve in any capacity as an airman in connection with any civil aircraft used in air commerce without an airman certificate authorizing him to act in such capacity, or in violation of the terms of any such certificate."

"Air commerce," it is explained, means "interstate, overseas, or foreign air commerce; or the transportation of mail by aircraft; or any operation or navigation of aircraft within the limits of any civil airway; or any operation or navigation of aircraft which directly affects interstate, overseas, or foreign air commerce, or which may endanger the safety of such commerce."

This means that for all ordinary flying you must have a pilot certificate granted by the Civil Aeronautics Authority. Various types of certificates are issued according to the general ratings [1] that follow:

(*a*) Student pilot rating.
(*b*) Private pilot rating.
(*c*) Commercial pilot rating.
(*d*) Airline pilot rating.

Apart from these, there are three types of glider pilot ratings.

[1] Formerly there were two additional general ratings — solo pilot rating and limited-commercial rating. These were discontinued on May 1, 1940.

Also there are two special pilot ratings, (*a*) instructor rating and (*b*) instrument rating. It is necessary to have the instructor rating for permission to give instruction in flying, and the instrument rating for permission to fly a plane by instruments (not by visual contact with the ground).

Requirements for pilot rating

To be eligible for any of the above pilot ratings the applicant must be at least 16 years old (18 years for private pilot rating or higher), of good moral character, able to read and write the English language, and up to requirements in physical condition. For ratings above the student-pilot grade, knowledge of flying and practical skill are necessary.

Becoming a pilot

In general, the order of procedure in becoming a pilot is as follows:

1. Receive at least eight hours of dual instruction (flying with an instructor) — enough to satisfy the instructor that you can safely solo (fly by yourself).
2. Obtain four photographs of yourself — two for the student pilot certificate and two for the private pilot certificate.
3. Make application for a student pilot certificate.
4. Pass the physical examination.
5. Receive the student pilot certificate (which permits you to solo).
6. Study the rules and regulations of the Civil Aeronautics Authority — particularly the air-traffic rules and satisfy the instructor that you know these and will fly in obedience to them when flying solo.
7. Practice at least thirty-five hours of solo flying — enough to satisfy the instructor that you can pass the flight test for the private pilot rating.

8. Study navigation and meteorology.

9. Make application for the private pilot certificate.

10. Pass the written examination in rules and regulations, navigation, and meteorology, and pass the flight test. These tests are given by a representative of the Civil Aeronautics Administration.

11. Receive a temporary private pilot certificate from the representative.

12. Receive a "permanent" private pilot certificate from the Civil Aeronautics Authority.

Application for student pilot certificate

In order to be permitted to fly a plane solo, so that you can practice for the private pilot flight test, it is required that you have a student pilot certificate.

Application for a student pilot certificate is made on a prescribed form, to an authorized medical examiner of the Civil Aeronautics Board. Attached to the application there must be two identical full-face pictures of yourself, measuring $1\frac{1}{2}$ inches by 2 inches.

When you have passed the physical examination, the medical examiner will issue to you a temporary student pilot certificate. Later you will receive the official certificate from the Civil Aeronautics Authority at Washington.

Before you may "solo," the instructor must certify by endorsement on your certificate that you have had at least 8 hours of dual flight time and that in his opinion you are able to solo.

Pilot logbook

A pilot must keep a record in a *pilot logbook* of all flight time, and a student pilot must do the same. A suitable logbook designed for this purpose can be purchased.

The entry for each flight must show —

(1) the make and model of aircraft flown,

(2) the type and weight-and-engine classification of the aircraft,

(3) the aircraft certificate number,

(4) the duration of the flight,

(5) the points between which the flight was made,

(6) whether it was an "instrument flight" and whether a night flight.

A student's logbook must distinguish dual from solo time; and it must indicate the nature of the maneuvers practiced, including cross-country flight. The entries in the student's logbook must be initialed by the instructor.

Solo time

A student may count as solo time only time in which he is the only occupant of the plane during flight. A pilot holding a higher certificate than a student certificate sometimes requires further instruction called "check time"; but he may count check time as solo time even though he is accompanied by an instructor, provided the instructor does not touch the controls.

Private pilot rating

To obtain the *private pilot rating*, a pilot must have logged at least 35 hours of solo time, of which at least 5 hours were logged within the preceding 60 days.

The flight time must include 5 hours of cross-country flying. At least 3 hours of the 5 must have been solo flying time; and there must have been at least one flight over a course of not less than 50 miles, with at least two full-stop landings at different points on the course. This cross-country flight must be certified to by some person or persons, other than the candidate, having direct knowledge of it. It

is desirable that someone at each airport visited should do the certifying.

Flight test

The applicant for private pilot rating must show in a flight test that he is proficient in the following maneuvers:

1. A series of three landings, without power, from an altitude not to exceed 1000 feet, after a 180-degree turn, the airplane touching the ground in normal landing attitude beyond and within 300 feet of a line designated by the inspector. (Fig. 321.)

2. A spiral of not less than three full turns, in each direction, without power, in a banked attitude of at least 60 degrees.

3. A series of three "shallow" figure eights and three "steep" figure eights, either "on-pylon" or "around pylon" (circular), with a total variation in altitude not to exceed 200 feet. The shallow and circular eights appear as shown in Figure 322.

4. One 720-degree power turn in each direction in a banked attitude of at least 60 degrees, with a total variation of altitude not to exceed 200 feet.

5. A right-hand and a left-hand spin, each of at least one full turn.

6. Coördination exercises, straight climbs, climbing turns, slips, and emergency maneuvers such as simulated forced landings, recovery from stalls entered from both level and steeply banked attitudes, and such other maneuvers as the inspector may deem necessary and appropriate to demonstrate the competency of the applicant.

The above flight test maneuvers are specified in a Civil Aeronautics Board bulletin which became effective March 11, 1941, entitled "Amending Aeronautical Skill Requirements for Private Pilot and Commercial Pilot Certificates."

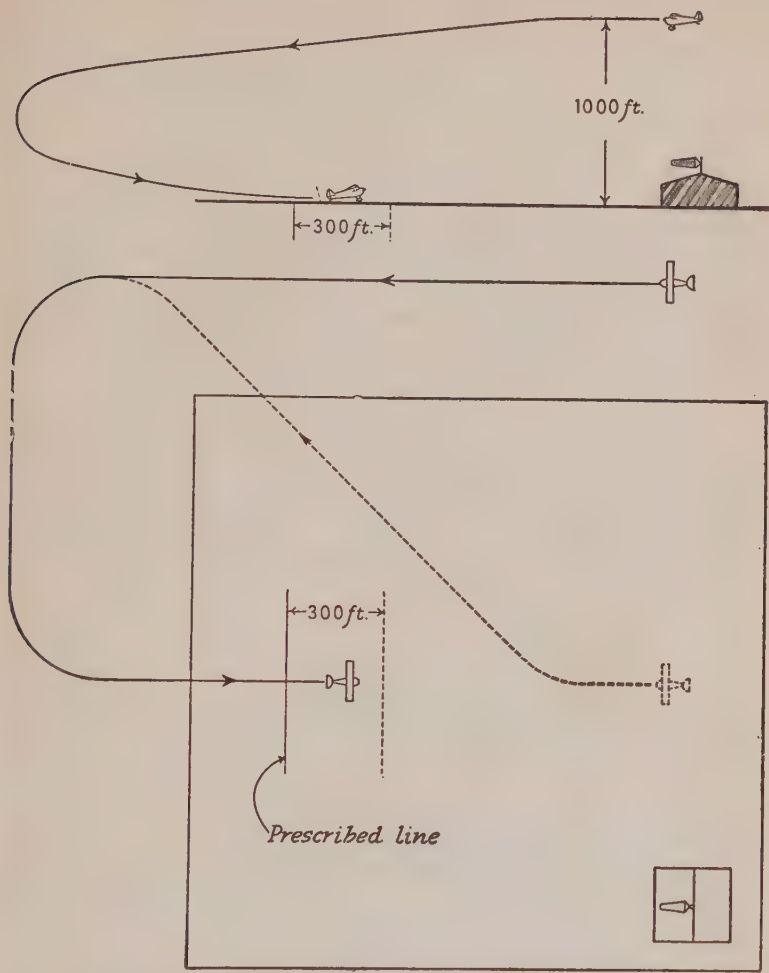


FIG. 321. The 180-degree turn with precision landing.

Earlier, in landing maneuvers, it was customary to require the pilot to close the throttle and begin the glide directly above the airport, as shown by the dotted line in Figure 321 (possibly even directly above the designated line on the airport). The amended regulations are interpreted

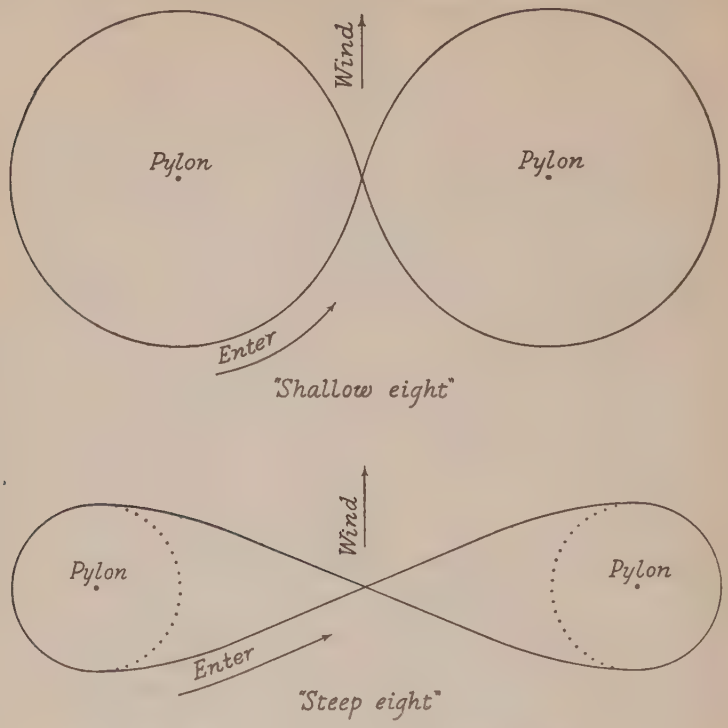


FIG. 322. Shallow and steep figure eights.

by inspectors as permitting the "side approach," as shown by the full line in the figure.

An inspector may choose different altitudes, such as 600 feet, 800 feet, and 1000 feet, at which the pilot is to throttle the engine for the three landings.

The candidate for a private pilot certificate must also pass a written examination on air-traffic rules, navigation, and meteorology.

The private pilot certificate is valid for one year and renewable. It permits the holder to pilot an aircraft of a particular weight-and-engine classification, carrying passengers but not for hire.

Airman certificate

A sample airman certificate (private pilot certificate) is shown in Figure 323.

Airman rating record

In addition to the airman certificate the pilot receives an *airman rating record* which specifies the class and type of plane which the pilot is permitted to fly, and gives the pilot's ratings with limitations. A sample airman rating record is shown in Figure 324.

Weight-and-engine classification

The "weight-and-engine classification," based on the weight of the plane and the number of engines, is given in Table 21. (S = Single-engine and M = Multi-engine.)

TABLE 21

WEIGHT-AND-ENGINE CLASSIFICATION

CLASS	GROSS WEIGHT	NO. OF ENGINES
1	1300 pounds or less	1
2S	1300 pounds to 4000 pounds	1
2M	1300 pounds to 4000 pounds	2 or more
3S	4000 pounds to 10,000 pounds	1
3M	4000 pounds to 10,000 pounds	2 or more
4S	10,000 pounds to 25,000 pounds	1
4M	10,000 pounds to 25,000 pounds	2 or more
5	Over 25,000 pounds	Any

The airman rating record states also whether the pilot may fly a land plane or a water plane (seaplane). The symbol "2S–LAND" on a record means that the pilot may operate a land plane of Class 2S.

Form 348
Rev. 1-1-40

UNITED STATES OF AMERICA
CIVIL AERONAUTICS AUTHORITY
WASHINGTON, D. C.

C-4/2/41

AIRMAN CERTIFICATE NO. 77777

This certifies that JOHN DOE is properly qualified and is physically able to perform the duties of PRIVATE PILOT

Address 1111 KING STREET
ARLINGTON VIRGINIA

DATE OF BIRTH	WEIGHT	HEIGHT	HAIR	EYES	SEX
4-17-16	180	6'1"	BLOND	BLUE	MALE

THIS CERTIFICATE is of 60 days' duration and, unless the holder hereof is otherwise notified by the Authority within such period, shall continue in effect indefinitely thereafter, unless suspended or revoked by the Authority, except that it shall immediately expire (1) at the end of each TWELVE months' period after the date of issuance hereof if the holder of this certificate fails to secure an endorsement by an authorized Inspector of the Authority within the last 45 days of each such period, or (2) at any time an authorized Inspector of the Authority shall refuse to endorse this certificate after inspection or examination.

Endorsement Refused:
Date:
Inspector, Civil Aeronautics Authority

Date of Issuance APRIL 17 1941
By direction of the Authority:
Signature: Clarke Conway
Title CHIEF, CERTIFICATE SECTION

This certificate is not valid unless there is attached hereto the appropriate Rating Record bearing the above number. Any alteration of this certificate is punishable by a fine of not exceeding $1,000 or imprisonment not exceeding three years, or both.

(Over) Signature of Holder:

FIG. 323. Airman certificate.

Form 545
1-1-40

UNITED STATES OF AMERICA
CIVIL AERONAUTICS AUTHORITY
WASHINGTON, D. C.

AIRMAN RATING RECORD NO. 77777

This Rating Record is not valid unless accompanied by the appropriate certificate bearing the above number.

Name JOHN DOE
Address 1111 KING STREET
ARLINGTON VIRGINIA

RATINGS WITH LIMITATIONS

2S - LAND
PRIVILEGES OF C A R 20.616 ACCORDED
HOLDER SHALL WEAR CORRECTING LENSES
WHILE OPERATING AIRCRAFT

By direction of the Authority: APRIL 17 1941 (Date of Issuance)
Clarke Conway (Signature) CHIEF CERTIFICATE SECTION (Title)

Any change of address should be endorsed on reverse side hereof but only after written notice has been mailed to the Civil Aeronautics Authority, Washington, D.C. Any alteration of this form may result in the suspension or revocation of the Certificate to which this form is attached. (Over)

FIG. 324. Airman rating record

Commercial pilot rating

To obtain the commercial pilot rating, the pilot must have logged at least 200 hours of solo flight. Commercial certificates are valid for only 6 months, but are renewable.

Airline pilot ratings require also that the holder have an instrument rating.

Dual controls inoperative

Only a pilot with an instructor rating may give instruction even without charge; and it is not permissible for a private pilot without an instructor rating to carry a passenger while dual controls are present and operative, unless the passenger has a private pilot rating or higher rating. Hence for carrying ordinary passengers a private pilot must remove the controls not used by him.

Piloting other planes

A private pilot may fly a plane of another weight-and-engine classification than that stated on his certificate, provided he does so under specified conditions — as not carrying an ordinary passenger.

Carry your certificate with you

The pilot certificate is like a driver's license. It is required that a pilot when piloting aircraft have with him at all times his pilot certificate, together with an identification card carrying his photograph. The certificate and identification card must be presented for inspection on the demand of any authorized person or at the reasonable request of any person.

Renewal

A pilot certificate may be renewed upon application made within 45 days prior to date of expiration (1) if the appli-

cant has had satisfactory recent flying practice and (2) has passed a physical examination within 14 months of the date of expiration of the certificate.

To renew a private pilot certificate, you must have had 15 hours of solo flight within the year preceding expiration of the certificate, or in lieu thereof 5 hours of specified flying practice within 45 days of the date of expiration of the certificate.

Instructor rating

An applicant for instructor rating must have a valid private pilot or commercial pilot certificate. He must have logged at least 200 hours of solo flight time and must pass a written examination and a flight test demonstrating that he has "practical and theoretical knowledge of flight instruction" and that he can "perform with precision and teach properly" the necessary flight maneuvers.

Instrument rating

An applicant for the instrument rating must pass a written examination in the use of instruments and other navigational aids and in meteorology as applied to weather analysis and forecasting. He must also pass a rigid flight test accomplished solely by instruments. He must have a valid private pilot or commercial pilot certificate and must have logged 200 hours of solo-flight time, including 20 hours of instrument-flight instruction and practice.

Questions

1. What are the four airplane pilot ratings?
2. Name two special pilot ratings which a pilot may have in addition to a regular pilot rating.
3. What are the requirements for a student pilot rating?
4. What is a pilot logbook and what information does it contain?

5. What is meant by solo flying?
6. What are the requirements for the private pilot rating?
7. What maneuvers are included in a private pilot flight test?
8. What different weight-and-engine classifications are there?
9. Under what conditions may a plane be flown with dual controls operative?
10. Under what conditions may a pilot certificate be renewed?

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AIRCRAFT CERTIFICATION

ALL aircraft operated in the United States, with a few exceptions, must be *registered* by the Administrator of the Civil Aeronautics Authority. The exceptions include aircraft of the national defense forces and aircraft of foreign registry.

It is unlawful for any person to operate or navigate any aircraft eligible for registration unless the aircraft is registered by its *owner*.

Application for the registration of an aircraft must be made upon the form prescribed and furnished by the Administrator, and must be accompanied by proper evidence that the applicant really owns the aircraft which he seeks to register. The owner must be a citizen of the United States.

Registration certificate

When an aircraft is registered, the owner receives a registration certificate. The registration certificate when received is theoretically of 60 days' duration, but the regulations provide that unless the Administrator notifies the holder of the certificate to the contrary within the 60 days, the registration certificate continues to be valid and in effect unless —

(1) the ownership of the aircraft is transferred,

(2) the aircraft is re-registered under the laws of some other country,

(3) the registration of the aircraft is canceled at the written request of the owner, or

(4) the aircraft is totally destroyed or scrapped.

If any one of these things happens, the registration immediately expires.

A sample aircraft registration certificate is shown in Figure 325.

Invalidation

Any registration of an aircraft becomes null and void if at the time of registration (1) the aircraft was registered under the laws of any foreign country, or (2) the person registered as owner was not the true and lawful owner of the aircraft, or (3) the person registered as owner was not a citizen of the United States, or (4) if the interest in the aircraft of the person registered as owner was created by a transaction not entered into in good faith.

Transfer

A registration certificate is not transferable. In general, if an aircraft is sold, the new purchaser must himself apply for a certificate of registration in his own name.

It takes time for the new owner to receive the new certificate; hence the regulations provide that upon transfer of ownership of aircraft the seller must endorse the registration certificate in the manner specified on it and must deliver the endorsed registration certificate to the purchaser. This done, the purchaser may operate the aircraft for 60 days from the date of the transfer of ownership. But if he has not by that time received the certificate, he may no longer operate the aircraft. It is important, therefore, to apply for registration certificate immediately after purchase, if you plan to keep the aircraft.

As just stated, the general rule is for the new owner to apply for a registration certificate. However, special provision is made for the benefit of dealers, and of any person

who may not intend to keep the plane more than a few days. If such a purchaser has received the endorsed registration certificate of the prior owner, and if the purchaser notifies the Administrator in writing that he has bought the plane, giving the date and his name and address, he may operate the plane for 60 days without applying for a registration certificate. He may sell the plane during that time and endorse the registration certificate and give it to the new purchaser. This new purchaser may then apply for a registration certificate in his own name or notify the Administrator of his purchase, as above; and he may use the aircraft for 60 days after the day he bought it, or sell it and endorse the certificate.

Airworthiness certificate

An airworthiness certificate is a certificate issued by the Administrator of the Civil Aeronautics Authority testifying that the plane is airworthy — safe to fly. It is unlawful for any civil aircraft to be operated in air commerce unless there is an airworthiness certificate currently in effect for the aircraft.

A sample aircraft airworthiness certificate is shown in Figure 326.

Application

Application for an airworthiness certificate may be made for any aircraft that is registered as an aircraft of the United States. Application must be made by the registered owner of the aircraft, on the form prescribed and furnished by the Administrator.

Inspection and certification

Before the airworthiness certificate is issued the aircraft is inspected by a representative of the Administrator to de-

FORM 500
1-1-40

UNITED STATES OF AMERICA
CIVIL AERONAUTICS AUTHORITY
WASHINGTON D C

THIS CERTIFICATE MUST BE CARRIED IN THE AIRCRAFT AT ALL TIMES

AIRCRAFT REGISTRATION CERTIFICATE NO. 00000

REGISTERED OWNER

JOHN DOE
1773 WASHINGTON LANE
BRADFORD UTAH

MAKE AND MODEL AERONCA 65-CA SERIAL NO. 000

WHEREAS IT HAS BEEN DECLARED THAT THE ABOVE DESCRIBED AIRCRAFT IS NOT REGISTERED UNDER THE LAWS OF ANY FOREIGN COUNTRY AND IS OWNED BY A CITIZEN OF THE UNITED STATES IT IS CERTIFIED THAT SUCH AIRCRAFT HAS BEEN DULY ENTERED ON THE AIRCRAFT REGISTER OF THE CIVIL AERONAUTICS AUTHORITY OF THE UNITED STATES OF AMERICA IN ACCORDANCE WITH THE CIVIL AERONAUTICS ACT OF 1938 AND THE REGULATIONS ISSUED PURSUANT THERETO.

DURATION

THIS CERTIFICATE IS OF 60 DAYS DURATION AND, UNLESS THE HOLDER HEREOF IS OTHERWISE NOTIFIED BY THE AUTHORITY WITHIN SUCH PERIOD SHALL CONTINUE IN EFFECT INDEFINITELY THEREAFTER EXCEPT THAT IT SHALL IMMEDIATELY EXPIRE UPON THE DATE (1) THE OWNERSHIP OF THE AIRCRAFT IS TRANSFERRED (2) THE AIRCRAFT IS REGISTERED UNDER THE LAWS OF ANY FOREIGN COUNTRY (3) THE REGISTRATION OF THE AIRCRAFT IS CANCELLED AT THE WRITTEN REQUEST OF THE OWNER OR (4) THE AIRCRAFT IS TOTALLY DESTROYED OR SCRAPPED

ISSUED APRIL 11 1941

BY DIRECTION OF THE AUTHORITY:

(OVER)

(Signed) Richard Roe
AERONAUTICAL INSPECTOR

ANY ALTERATION OF THIS CERTIFICATE IS PUNISHABLE BY A FINE OF NOT EXCEEDING $1,000 OR IMPRISONMENT NOT EXCEEDING THREE YEARS, OR BOTH.

3-41

FIG. 325. Aircraft registration certificate.

Form 308
1-1-40

UNITED STATES OF AMERICA
CIVIL AERONAUTICS AUTHORITY
WASHINGTON, D. C.

This Certificate Must Be Carried in the Aircraft At All Times

AIRCRAFT AIRWORTHINESS CERTIFICATE NO. 00000

This certifies that AERONCA 65-CA manufacturer's serial No. 000, has been inspected and this day found to be in condition for safe operation when operated and maintained in accordance with the regulations and practices prescribed by the Authority.

The aircraft for which this certificate is issued (a) shall not be operated unless there is attached hereto the currently effective Aircraft Operation Record issued by the Authority for the aircraft, and (b) shall not be operated in flight unless a pilot possessed of a currently effective and appropriate pilot certificate issued by the Authority, is in command.

This certificate is of 60 days' duration and, unless the holder hereof is otherwise notified by the Authority within such period, shall continue in effect indefinitely thereafter, unless suspended, revoked, or cancelled by the Authority, except that it shall immediately expire (1) at the end of ONE YEAR after the date of issuance of this certificate or after the date of last endorsement hereof, whichever is later, if within such period this aircraft is not examined or inspected by an authorized inspector for the Authority, or (2) at any time an authorized inspector of the Authority shall refuse to endorse this certificate after examination or inspection.

By direction of the Authority:

Refusal to endorse: _____
Inspector of the Authority

Date: _____

(Signed) Richard Roe
AERONAUTICAL INSPECTOR

Date of Issuance:

APRIL 11 1941

Any alteration of this certificate is punishable by a fine of not exceeding $1,000, or imprisonment not exceeding three years, or both.

3-41 (over)

FIG. 326. Aircraft airworthiness certificate.

termine whether it complies with the requirements specified in the Civil Air Regulations.

Manufacturers of aircraft may obtain airworthiness certificates when they have shown that aircraft were manufactured exactly in accordance with approved plans under *type* certificates and *production* certificates.

Duration

An airworthiness certificate is theoretically good for 60 days; but unless suspended, revoked, or canceled, it continues to be in effect for a period specified upon it — usually one year.

If the holder wishes to have the airworthiness certificate continue in effect after the specified period, he may have the aircraft inspected by an inspector for the Administrator before the end of the period. If the inspector finds the craft airworthy and endorses the certificate to that effect, it is good for another period of the specified length beginning on the day of endorsement, unless it is suspended, revoked, or canceled.

If the inspector does not endorse the certificate, presumably because he does not find the craft airworthy, the certificate immediately expires.

If the holder of the certificate fails to have the necessary inspection made during the period for which it is valid, the certificate expires at the end of the period.

An airworthiness certificate may be canceled upon written request of the registered owner of the aircraft.

Display of certificates

A registration certificate and an airworthiness certificate must be carried at all times in the aircraft for which they have been issued; and they must be presented upon the request of any authorized representative of the Adminis-

trator or of the Civil Aeronautics Board, or upon the request of any state or municipal official charged with enforcing local regulations of aviation involving compliance with Federal laws.

Surrender of certificates

Upon cancellation, suspension, revocation, expiration, or invalidation of a registered certificate or of an airworthiness certificate, the owner of the aircraft must, upon request, surrender such certificate to any representative of the Administrator.

Identification marks

In general, no aircraft shall be operated within the United States unless it displays an identification mark assigned thereto by the Administrator.

The identification marks assigned by the Administrator are as follows:

NC. A certificated aircraft which has fully complied with the minimum airworthiness requirements specified in the Civil Air Regulations displays the roman capital letters NC followed by the registration number.

NR. A certificated aircraft which has not demonstrated compliance with the airworthiness requirements specified in the Civil Air Regulations, but which in the opinion of the Administrator is in condition for safe operation *for particular activities*, must display the roman capital letters NR followed by the registration number.

NX. A certificated aircraft which has not demonstrated compliance with the airworthiness requirements specified in the Civil Air Regulations, but which in the opinion of the Administrator is in condition for safe operation *for experimental purposes*, must display the roman capital letters NX followed by the registration number.

No letters. An uncertificated aircraft must display the registration number only.

Display of identification marks

The identification marks on conventional aircraft must be displayed on the lower surface of the left wing and on the upper surface of the right wing, with the top of the letters toward the leading edge. The mark must be located also on both sides of the vertical tail surface of all conventional aircraft.

Certificated aircraft; violations

An aircraft for which an airworthiness certificate is currently in effect is called a *certificated aircraft.*

It is unlawful for any aircraft to be operated in violation of the terms of the certificate of airworthiness which was issued for that aircraft.

The owner of a certificated aircraft must not permit any person to operate such aircraft unless such person possesses an appropriate and currently effective pilot certificate.

Aircraft-operations record

A certificated aircraft may not be operated unless there is attached to the airworthiness certificate the appropriate aircraft-operations record. This is a record issued by the Administrator for an aircraft, stating the limits for the safe operation of that aircraft. The aircraft may not be operated in violation of any of the limitations set forth in the aircraft-operations record.

Aircraft and engine logbooks

The registered owner of a certificated aircraft is responsible for the maintenance of a logbook for the aircraft and a logbook for each engine installed therein. Such logbooks

must be current, accurate, legible, and permanent records. These logbooks are distinct from the pilot logbooks discussed in the preceding chapter.

The *aircraft logbook* must contain a complete history of the operation of the aircraft. Among other things it must include —

(*a*) flight time of the aircraft,

(*b*) reports of periodic inspections and other inspections, and

(*c*) reports of repairs and any alteration of the aircraft structure and propellers.

Each *engine logbook* must contain a complete history of the operation of the engine to which it pertains. Among other things it must include —

(*a*) the running time of the engine in flight,

(*b*) reports of periodic inspections and other inspections, and

(*c*) reports of repairs and alterations of the engine.

Disposition of logbooks

The logbooks required (except for air-carrier aircraft) must be carried in the aircraft at all times when it is away from the landing area regularly used as its base of operations. They must be presented for inspection, upon demand and reasonable notice, to any representative of the Administrator or of the Civil Aeronautics Board, or to any state or municipal officer enforcing local regulations of aviation involving compliance with Federal laws.

Periodic inspection

A certificated aircraft must not be operated unless, within the last 100 hours of flight time, it has been given what is called a *periodic inspection*. The inspection must be made by a person having a currently effective mechanic certificate

permitting the person to work on an aircraft; and it must be made in accordance with a report called the Periodic Aircraft Inspection Report, a form prescribed and furnished by the Administrator.

The result of such inspection must be entered in the aircraft logbook and on the Periodic Aircraft Inspection Report form over the signature and certificate number of the person making the inspection.

Periodic inspection preceding endorsement of airworthiness certificate

Before an aircraft is submitted to the representative of the Administrator (inspector) for an inspection of the airworthiness of the aircraft for the purpose of extending the period of operation by endorsement of the airworthiness certificate, the aircraft must be given a *periodic inspection.* The registered owner is responsible for having this inspection made, by a person having a proper mechanic certificate, within a reasonable time before the aircraft is presented to the inspector.

Damage or alteration

If a certificated aircraft is so damaged as to require a major repair or if it undergoes any major alteration, the aircraft must not be operated until examined, inspected, and approved by a representative of the Administrator.

When a certificated aircraft, or any engine or propeller thereof, has undergone a major repair or a major alteration, before the aircraft may carry any passengers it must be test-flown by a pilot having not less than 200 solo hours of flight time and holding a rating appropriate for the aircraft to be test-flown.

The results of all the above-mentioned inspections must be entered in the aircraft logbook over the signature and certificate number of the person making the inspection.

Notification and report of accidents

When an aircraft accident causes death or serious injury to a person or substantial damage to property, the airman concerned and the registered owner or operator of the aircraft, if physically able, must notify the Civil Aeronautics Board of the accident immediately. This they must do in person or by telephone or telegraph, stating the registered number of the aircraft and the time, place, and nature of the accident.

All such accidents must also be reported on accident report forms provided by the Civil Aeronautics Board. A report must include all pertinent information relating to the accident, for which space is provided on the report form. The report must be made without delay by or on behalf of the airman, and by or on behalf of the registered owner of the aircraft.

Except for urgent reasons no aircraft or aircraft part involved in an accident in air commerce may be moved or disturbed until released by the Civil Aeronautics Board.

QUESTIONS

1. What is meant by the registration of aircraft?
2. Who may apply for the registration of an aircraft?
3. What is a registration certificate?
4. Under what conditions does a registration certificate become invalid?
5. What procedure must be followed when the ownership of an aircraft is transferred?
6. What is an airworthiness certificate?
7. What procedure must the owner of an aircraft follow in order to obtain an airworthiness certificate?
8. What is the duration of an airworthiness certificate?
9. Where is the airworthiness certificate kept?
10. What is the meaning of NC, NR, and NX in connection with the certification of aircraft?

11. What is an identification mark and where is it displayed?
12. What is an aircraft-operations record?
13. What are aircraft and engine logbooks and what do they contain?
14. Where are aircraft and engine logbooks kept?
15. What is a periodic inspection?
16. What is done in the case of damage or alteration of an aircraft?
17. Who is responsible for reporting aircraft accidents?
18. In what manner are aircraft accidents reported?

43

AIR-TRAFFIC RULES

WHEN you begin your solo flight practice you assume the responsibility of flying the plane safely; and to do this you must fly it in accordance with the rules governing flight, so that other pilots will know what to expect of you. Hence you must study the flight rules early — before you solo. The following air-traffic rules are among the principal ones that you need to know.

Certificates

No person shall pilot a civil aircraft unless possessed of a valid pilot's certificate of competency (Chapter 42), or in violation of any term, specification, or limitation of such certificate.

No civil aircraft shall be flown unless such aircraft is the subject of a valid aircraft registration and an airworthiness certificate or experimental certificate, or in violation of any such certificate. All aircraft must have and display a valid identification mark (number) assigned by the Civil Aeronautics Board (Chapter 42).

Method of taking off and landing

The following rules apply to take-off and landing:

(*a*) Aircraft shall observe the local air-field traffic rules.

(*b*) A take-off shall not be begun when there is any danger of collision with other aircraft during such take-off.

(*c*) Aircraft approaching for a landing shall circle the airport (to the left) unless otherwise instructed, sufficiently to observe other traffic.

(*d*) Aircraft approaching for a landing shall maintain a straight approach course, unless impracticable, for at least 1000 feet before crossing the boundary of the airport (Fig. 327).

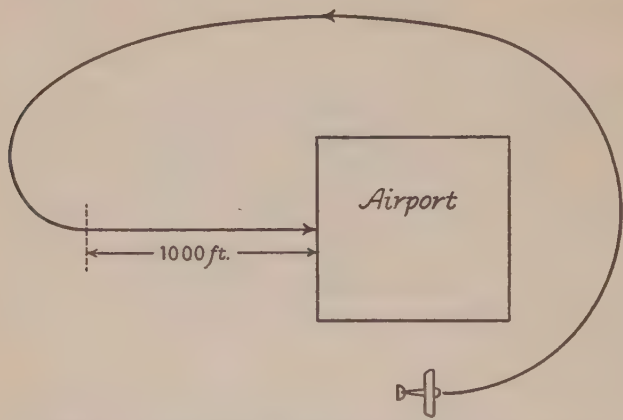


FIG. 327. A plane approaching an airport, in conformity with the air-traffic rules.

In approaching a landing area where there appears to be a congestion of air traffic, the pilot shall proceed with caution and ascertain before landing whether or not an air meet is in progress. A large ○ on the ground or on a hangar indicates that the field is open. A large × indicates that the field is closed.

Running motors

No aircraft engine shall be started or run unless a competent operator is in the aircraft attending the engine controls. Blocks, equipped with ropes or other suitable means of pulling them, shall be placed in front of the wheels before starting the engine, unless the aircraft is provided with adequate parking brakes and these are fully on.

Remember, this means that you may not start your own plane with no one in it or get out and leave the propeller

turning. If it is necessary to start the engine by turning the propeller, someone else must do this for you unless you have a competent person in the plane attending the controls while you start it, and you must always shut off the ignition before leaving the plane.

Right of way

The following rules govern right of way of aircraft:

(*a*) *Order.* Aircraft have the right of way in the following order — (1) free balloons, (2) gliders, (3) airships, and (4) airplanes. This means that an airplane pilot yields the right of way to all the other classes of aircraft.

(*b*) *Crossing.* When two aircraft are about to cross one another's path, the aircraft having the other on its left has the right of way. That is, you must give way to any plane approaching on your right (Fig. 328 (*a*)).

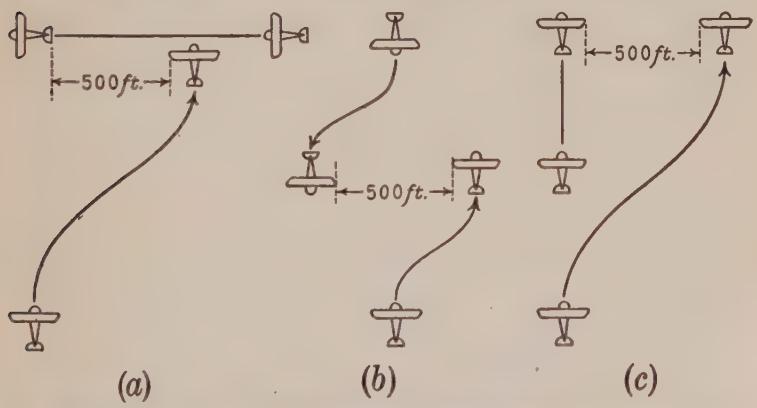


FIG. 328. One plane overtaking and passing another, in conformity with the air-traffic rules.

(*c*) *Approaching head on.* When two aircraft are approaching approximately head on, each pilot shall alter his course to the right so the aircraft will pass each other at least 500 feet apart (Fig. 328 (*b*)).

(*d*) *Overtaking.* An overtaken aircraft has the right of way, and the overtaking aircraft shall alter its course to the right (Fig. 328 (*c*)).

(*e*) *Landing.* In general, an aircraft landing has the right of way over other aircraft in flight or on the ground or water.

(*f*) *Relative height; landing.* When landing or maneuvering in preparation to land, the aircraft at the lower altitude has the right of way, except over aircraft landing in distress.

(*g*) *Distress landing.* An aircraft in distress attempting to land has the right of way over all other aircraft.

(*h*) *Proximity in flight.* Aircraft may not fly less than 500 feet apart, except by prearrangement between pilots.

Suppose you have the right of way over another plane. Remember that the other pilot may not see you, and that in any case he may not observe the rules for right of way. People have been killed maintaining their right of way, even on the ground! A wise rule to lay down for oneself is: *The other fellow always has the right of way.*

Minimum safe altitudes

Exclusive of taking off and landing, aircraft shall not be flown below the following minimum safe altitudes of flight:

3000 feet — minimum for flying directly over an airport;

1500 feet — minimum for completion of all acrobatics;

1000 feet — minimum for flying over congested areas in cities and towns (Fig. 329), open-air assemblages, Federal penal institutions, areas where high explosives are manufactured or stored, or any ground or water if the aircraft is making an instrument flight;

500 feet — minimum for flight over land (top of any hill or obstruction); and

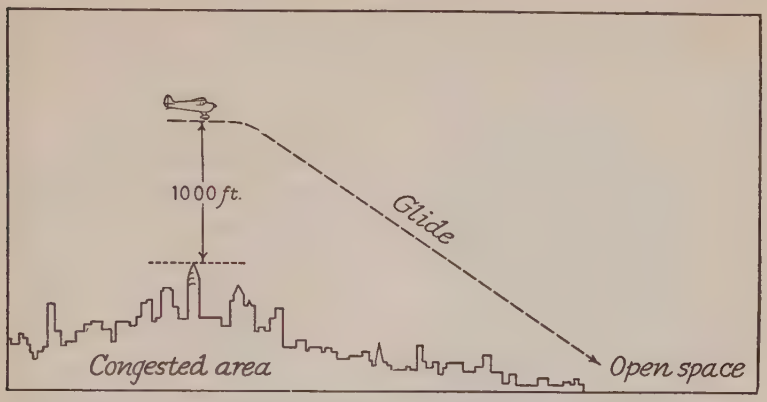


FIG. 329. The minimum altitude for flying over a congested area.

300 feet — minimum for flight of seaplanes over open water in daylight (500 feet at night).

The regulations require that you must be able at any moment to glide to an open space. To do so may require at times that you fly higher than the altitude given above.

Things forbidden

Nothing shall be dropped from an aircraft in flight other than fine sand, fine shot, fuel, or water.

Explosives, arms, or munitions of war may not, in general, be carried in civilian aircraft; but there are exceptions, as of arms for hunting and explosives for signals and flares.

No person who is under the influence of liquor, cocaine, or other habit-forming drug (except a medical patient under proper care, or in a case of emergency) may be carried in any aircraft. This applies to pilots, crew members, and passengers.

No parachute shall be carried ready for immediate use, unless it has been packed (repacked) within the preceding 60 days by a certificated parachute rigger. A tag showing the last date of packing must be kept available for examination in the pocket of the parachute case.

No aircraft may tow any other aircraft or object except by permission of the Civil Aeronautics Board.

Acrobatic flight

Any maneuvers not necessary to normal flight, such as stalls, spins, and loops, are called *acrobatic flight* (Fig. 330).

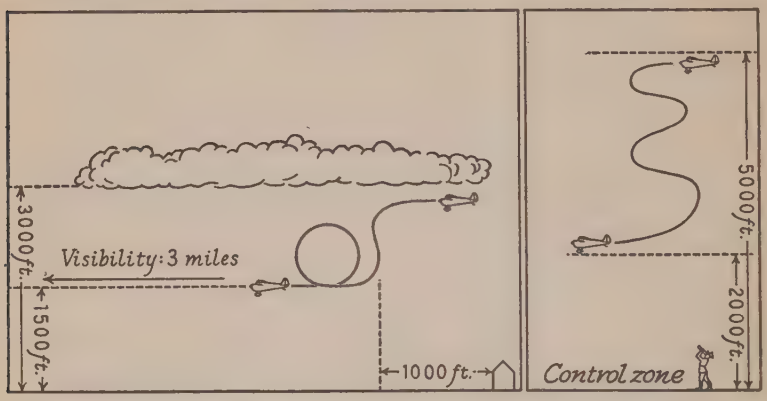


FIG. 330. The minimum altitude for acrobatics.

No person shall fly an aircraft acrobatically —

(*a*) over a congested area or an assembly or an airport;

(*b*) within 1000 feet horizontally thereof;

(*c*) under 1500 feet;

(*d*) in a control zone (page 597) except between 2000 and 5000 feet above ground or water and under the supervision of a Civil Aeronautics Board inspector observing flight tests;

(*e*) with visibility less than 3 miles;

(*f*) with ceiling less than 3000 feet;

(*g*) while carrying persons for hire, except an instructor with a student;

(*h*) without a parachute.

Use of the parachute

The canopy of a parachute, usually of silk, is attached by cords to a harness worn by the pilot (Fig. 331).

The parachute is kept folded up in a canvas case, and it is often arranged to be sat on by the pilot or parachutist. Sometimes you merely wear the harness, and attach the parachute quickly in case of emergency.

If it becomes necessary to bail out, the 'chutist leaps; and then, when fully clear of the plane, he jerks a ring to pull the *rip cord.* The action releases from the cover a small parachute. When this is opened by the air it pulls out the main parachute, which in turn opens up and checks the fall of the 'chutist.

Irving Air Chute Co., Inc.

FIG. 331. A parachutist during descent. Notice that he sits in the harness as if it were a swing. His hands are grasping the "risers."

A parachute may be steered to some extent. Thus, if a pilot wishes to cause the parachute to veer to the east, he pulls on the cords attached to the east side of the canopy. This causes the canopy to slope down toward the east slightly and hence to slip toward the east. On reaching the ground, if a wind is blowing the pilot pulls the cords going to the side of the canopy nearest the ground, causing the canopy to flatten out on the ground and not to drag the pilot.

It is of utmost importance that the parachute be correctly folded and packed, so that it will be sure to operate properly when used; that it never be allowed to get damaged by mildew, rust, or battery acid; and that it be at all times ready for immediate use. It is for this reason that the Civil

Aeronautics Board requires that no parachute be carried for use unless it has been packed by a certificated parachute rigger within the preceding 60 days.

Except in an emergency no parachute jump may be made —

(*a*) without an auxiliary (second) parachute ready for use;

(*b*) from less than 2000 feet above the ground;

(*c*) with intentionally delayed opening, except for safety;

(*d*) in a high wind; or

(*e*) near open water.

Night flying

Any flight between sunset and sunrise is considered as night flying. No night flight may be made —

(*a*) carrying passengers, unless the pilot has made five take-offs and landings at night within the preceding 90 days;

(*b*) for hire for a distance of more than 3 miles from a landing area, unless the plane is equipped with landing flares;

(*c*) without the following lights —

(1) two side lights (green on right and red on left) visible for 2 miles through an unbroken arc of 110° with straight ahead (Fig. 332).

(2) a white tail light, visible for 3 miles in an unbroken arc of 70° on each side of the longitudinal axis.

Definitions

You will need to be familiar with the following terms used in connection with air-traffic rules:

Civil airways. The air routes in the navigable air space considered suitable for interstate commerce are designated as "civil airways" by the Civil Aeronautics Board. The principal civil airways of the United States are shown on

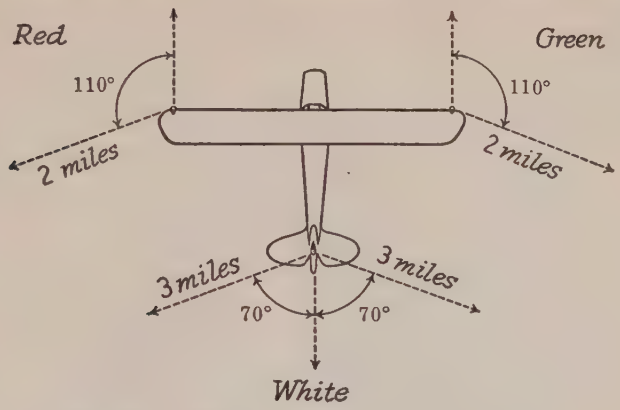


FIG. 332. The lights required for night flying.

the map in Figure 333. A civil airway comprises the area between two parallel lines, each 10 miles to the side of the direct route between airports, as shown in Figure 334.

Control airport. The Civil Aeronautics Board has designated some airports as "control airports" with authority to control the traffic in the region of the airport (zone).

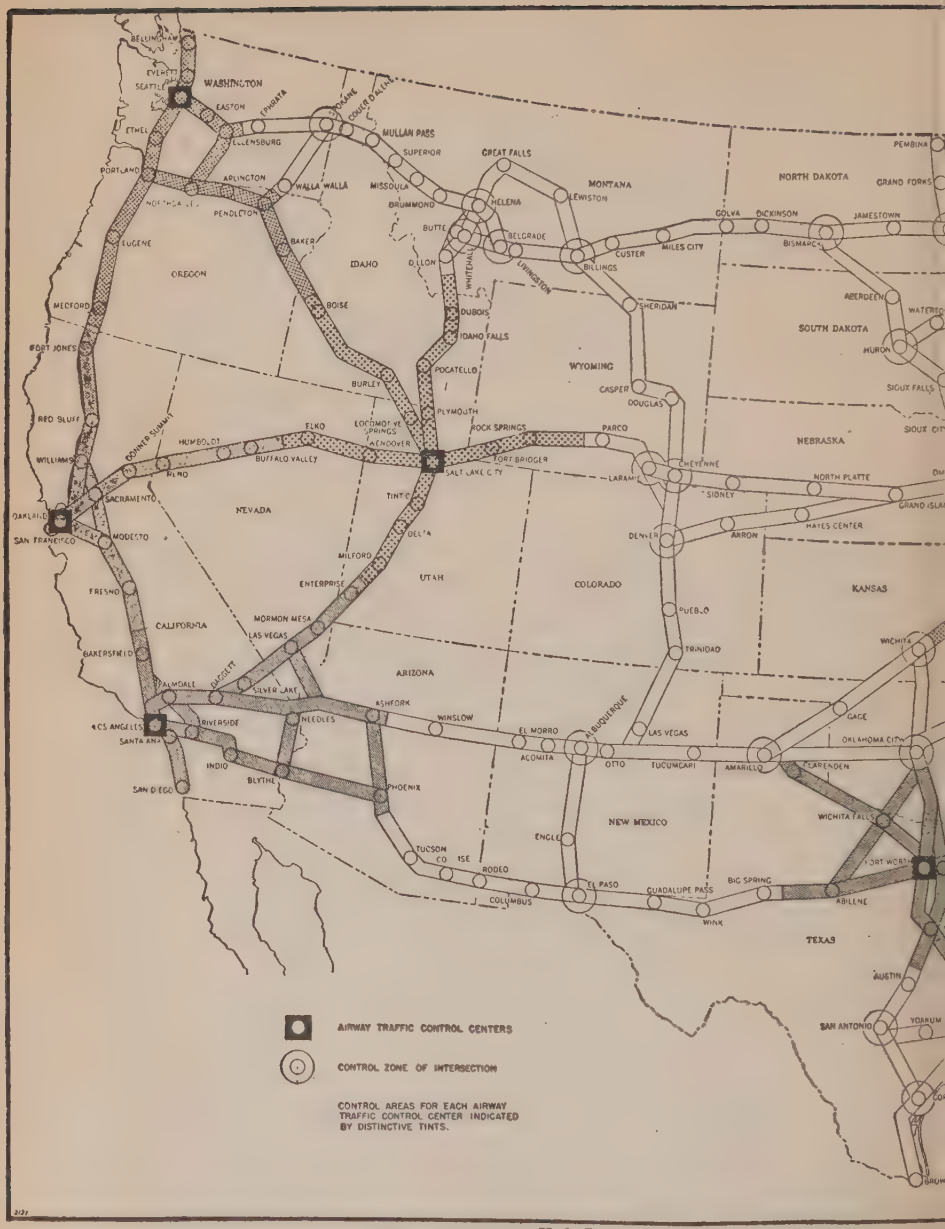
Control zone. The air space above a circle with a radius of 3 miles drawn from the center of the control airport, and within one-half mile of a line extended from the center of such airport to the radio range station established for the purpose of directing air traffic to such airport.

Control zone of intersection. A circle with 25-mile radius and a center at a control airport.

Airway traffic-control center. A station operated by the Board for the control of air traffic.

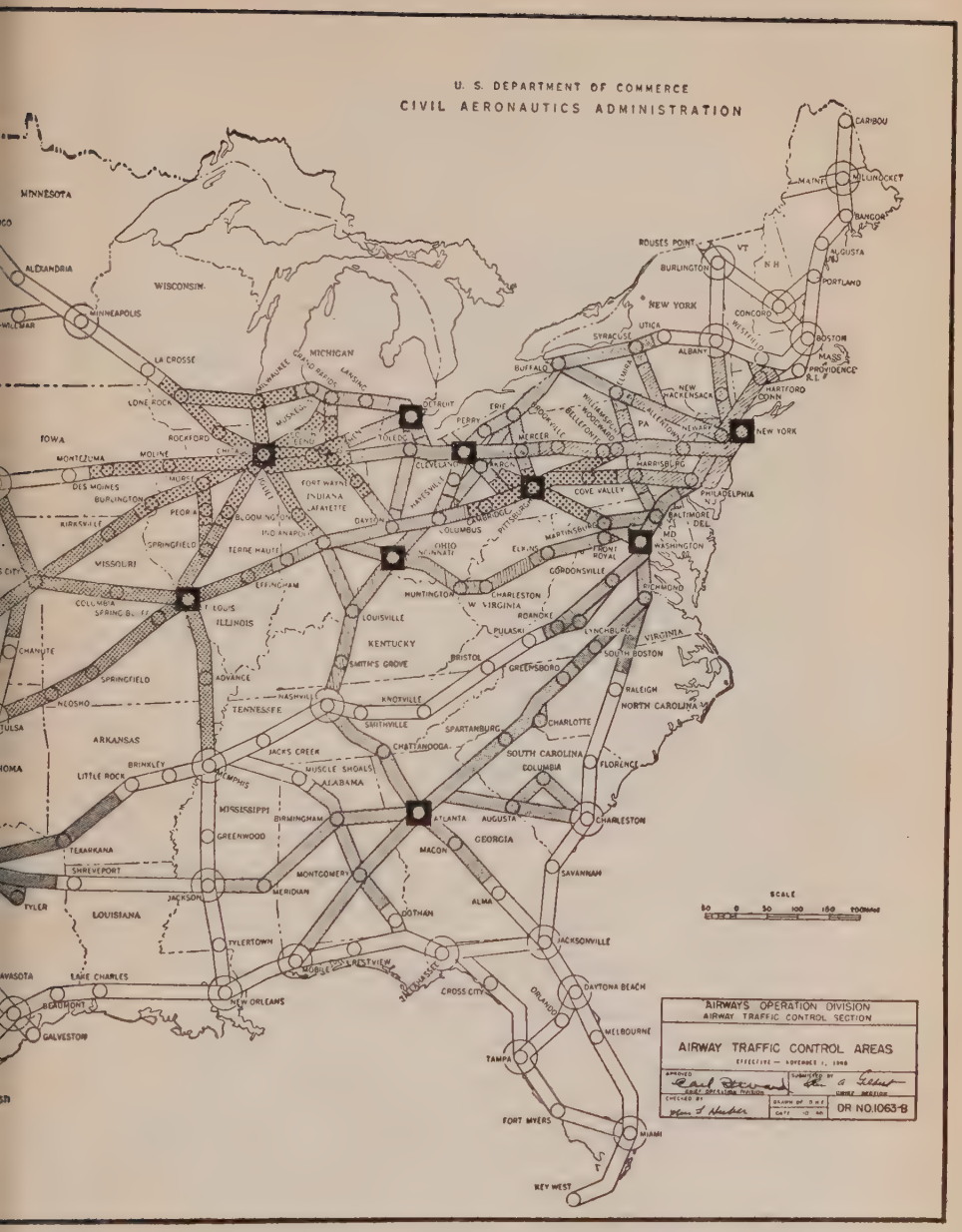
Airport control tower. A tower from which an operator can control the traffic at an airport. A control tower often has red and green signal lights, and sometimes a loud speaker.

Contact flight. Flight in which the pilot can always see the ground or water.



U. S. Department of Commerce, Civil Aeronautics Admi

FIG. 333. The civil airways of the United States.


U. S. DEPARTMENT OF COMMERCE
CIVIL AERONAUTICS ADMINISTRATION
AIRWAYS OPERATION DIVISION
AIRWAY TRAFFIC CONTROL SECTION
AIRWAY TRAFFIC CONTROL AREAS
DR NO.1063-B
SCALE
MINNESOTA
WISCONSIN
MICHIGAN
IOWA
MISSOURI
ILLINOIS
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
ALABAMA
GEORGIA
SOUTH CAROLINA
NORTH CAROLINA
VIRGINIA
W VIRGINIA
OHIO
INDIANA
NEW YORK
PA
MD
DEL
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VT
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MAINE
MASS
R.I.
CONN
LOUISIANA
TEXAS
ALEXANDRIA
MINNEAPOLIS
LA CROSSE
LONE ROCK
ROCKFORD
MOLINE
MONTEZUMA
DES MOINES
BURLINGTON
KIRKSVILLE
PEORIA
SPRINGFIELD
TERRE HAUTE
EFFINGHAM
COLUMBIA
CHANUTE
NEOSHO
TULSA
LITTLE ROCK
BRINKLEY
MEMPHIS
TEXARKANA
SHREVEPORT
TYLER
JACKSON
MERIDIAN
TYLERTOWN
LAKE CHARLES
BEAUMONT
GALVESTON
NEW ORLEANS
MOBILE
RESTVIEW
MONTGOMERY
DOTHAN
ALMA
JACKSONVILLE
CROSS CITY
ORLANDO
DAYTONA BEACH
MELBOURNE
TAMPA
FORT MYERS
MIAMI
KEY WEST
SAVANNAH
CHARLESTON
FLORENCE
COLUMBIA
AUGUSTA
ATLANTA
MACON
BIRMINGHAM
GREENWOOD
MUSCLE SHOALS
JACKS CREEK
CHATTANOOGA
SPARTANBURG
CHARLOTTE
RALEIGH
SOUTH BOSTON
LYNCHBURG
RICHMOND
GORDONSVILLE
FRONT ROYAL
MARTINSBURG
BALTIMORE
WASHINGTON
PHILADELPHIA
HARRISBURG
COVE VALLEY
NEWARK
NEW HACKENSACK
HARTFORD
PROVIDENCE
BOSTON
WESTFIELD
CONCORD
PORTLAND
AUGUSTA
BANGOR
MILLINOCKET
CARIBOU
ROUSES POINT
BURLINGTON
UTICA
SYRACUSE
ALBANY
BUFFALO
ERIE
PERRY
MERCER
BROOKVILLE
WILLIAMSPORT
WOODWARD
BELLEFONTE
ALLENTOWN
NEW YORK
CLEVELAND
AKRON
HAYESVILLE
COLUMBUS
CAMBRIDGE
PITTSBURGH
ELKINS
HUNTINGTON
CHARLESTON
ROANOKE
PULASKI
BRISTOL
GREENSBORO
KNOXVILLE
SMITHVILLE
NASHVILLE
SMITH'S GROVE
LOUISVILLE
ADVANCE
SPRINGFIELD
LANSING
GRAND RAPIDS
MILWAUKEE
MUSKEGON
TOLEDO
DETROIT
FORT WAYNE
LAFAYETTE
BLOOMINGTON
INDIANAPOLIS
DAYTON
CHICAGO
MURRAY
MONTEZUMA
DES MOINES
CHANUTE
TULSA
HOMA
TYLER
AVASOTA
CITY
SPRINGFIELD
MISSOURI
ILLINOIS
KENTUCKY
TENNESSEE
ARKANSAS
MISSISSIPPI
ALABAMA
GEORGIA
SOUTH CAROLINA
NORTH CAROLINA
VIRGINIA
W VIRGINIA
OHIO
INDIANA
NEW YORK
PA
MD
DEL
N J
VT
N H
MAINE
MASS
R.I.
CONN
LOUISIANA
TEXAS
MINNEAPOLIS
WILLMAR
ALEXANDRIA
LA CROSSE
LONE ROCK
ROCKFORD
MOLINE
MONTEZUMA
DES MOINES
BURLINGTON
KIRKSVILLE
PEORIA
SPRINGFIELD
TERRE HAUTE
EFFINGHAM
COLUMBIA
SPRING BLUFF
ST LOUIS
CHANUTE
NEOSHO
TULSA
LITTLE ROCK
BRINKLEY
MEMPHIS
TEXARKANA
SHREVEPORT
TYLER
JACKSON
MERIDIAN
LAKE CHARLES
BEAUMONT
GALVESTON
NEW ORLEANS
MOBILE
RESTVIEW
MONTGOMERY
DOTHAN
ALMA
JACKSONVILLE
CROSS CITY
ORLANDO
DAYTONA BEACH
MELBOURNE
TAMPA
FORT MYERS
MIAMI
KEY WEST
SAVANNAH
CHARLESTON
FLORENCE
COLUMBIA
AUGUSTA
ATLANTA
MACON
BIRMINGHAM
GREENWOOD
MUSCLE SHOALS
JACKS CREEK
CHATTANOOGA
SPARTANBURG
CHARLOTTE
RALEIGH
SOUTH BOSTON
LYNCHBURG
RICHMOND
GORDONSVILLE
FRONT ROYAL
MARTINSBURG
BALTIMORE
WASHINGTON
PHILADELPHIA
HARRISBURG
COVE VALLEY
NEWARK
NEW HACKENSACK
HARTFORD
PROVIDENCE
BOSTON
WESTFIELD
CONCORD
PORTLAND
AUGUSTA
BANGOR
MILLINOCKET
CARIBOU
ROUSES POINT
BURLINGTON
UTICA
SYRACUSE
ALBANY
BUFFALO
ERIE
PERRY
MERCER
BROOKVILLE
WILLIAMSPORT
WOODWARD
BELLEFONTE
ALLENTOWN
NEW YORK
CLEVELAND
AKRON
HAYESVILLE
COLUMBUS
CAMBRIDGE
PITTSBURGH
ELKINS
HUNTINGTON
CHARLESTON
ROANOKE
PULASKI
BRISTOL
GREENSBORO
KNOXVILLE
SMITHVILLE
NASHVILLE
SMITH'S GROVE
LOUISVILLE
ADVANCE
LANSING
GRAND RAPIDS
MILWAUKEE
MUSKEGON
TOLEDO
DETROIT
FORT WAYNE
LAFAYETTE
BLOOMINGTON
INDIANAPOLIS
DAYTON
CHICAGO
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DES MOINES
CHANUTE
TULSA
HOMA
TYLER
AVASOTA
CITY
SCALE
50 0 50 100 150 200 Miles

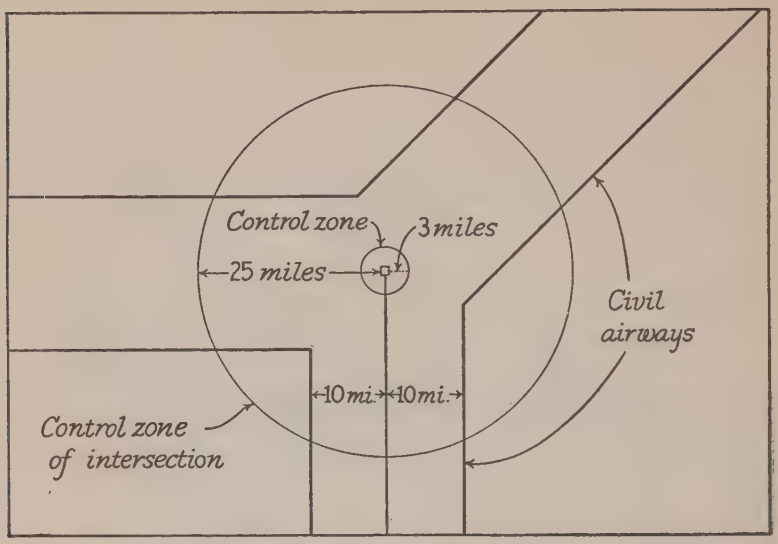


FIG. 334. Civil airways; control zone; control zone of intersection.

Instrument flight. Flight in which the pilot cannot always see the ground and must fly partly or wholly with the aid of instruments.

Over-the-top flight. Flight above an overcast cloud formation (above a solid cloud layer, or a layer such that the pilot is unable to see the ground at all times).

Ceiling. Distance from the cloud base to the ground when the clouds cover more than half the sky; otherwise the ceiling is "unlimited."

Daylight. Hours between sunrise and sunset.

Night. Hours between sunset and sunrise.

Visibility. Greatest distance toward the horizon at which conspicuous objects can be seen and identified.

Contact-flight rules. Rules that must be observed in all contact flight, definitely distinguished from *instrument-flight rules.*

Instrument-flight rules. Rules governing all instrument flight.

Weather minimums — contact flight

When flying "without instruments," you must observe the following contact-flight weather minimums:

(*a*) *Ceiling.* Minimum 800 feet (Fig. 335).

EXCEPTION. At night or with precipitation, 1000 feet.

(*b*) *Distance from cloud layers.* Minimum distance above or below cloud layer, 300 feet (Fig. 335).

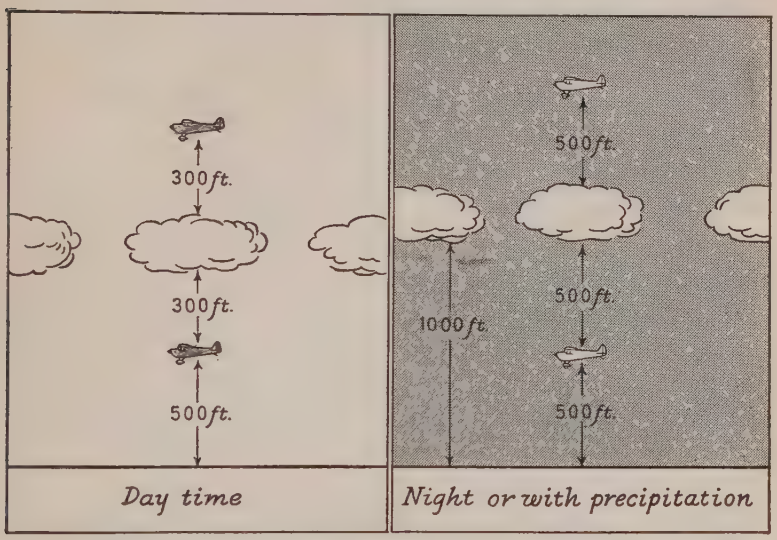


FIG. 335. Minimum altitudes required, with reference to time of day, weather, height of ceiling, and vertical distance from clouds.

EXCEPTION. At night or with precipitation, 500 feet.

(*c*) *Visibility.* Minimum 3 miles (Figs. 336 and 337).

EXCEPTION 1. A control-tower operator may at his discretion permit flight in a control zone with a minimum of not less than 1 mile in daytime and 2 miles at night. On the other hand, he may suspend flight in the control zone at his discretion in the interest of safety. (Fig. 336.)

EXCEPTION 2. Outside a control zone, flight at or below 1000 feet may be made with a minimum visibility of 1 mile in the daytime or 2 miles at night. (Fig. 337.)

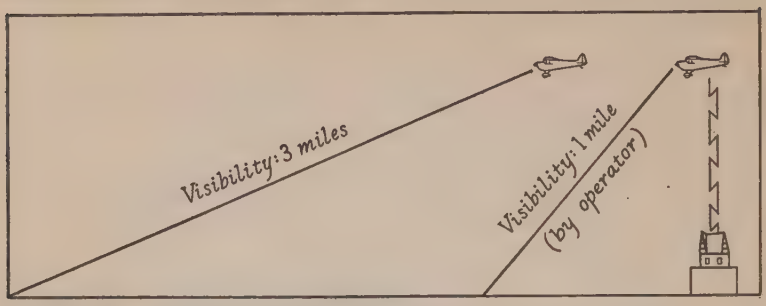


FIG. 336. Visibility minimums within a control zone.

(*d*) *Horizontal distance from clouds.* Minimum 2000 feet (Fig. 338).

(*e*) *Over the top.* No flight shall be made over the top under contact-flight rules. This means that a pilot must have the instruments for instrument flying and an instrument rating in order to fly "over the top."

If the weather changes while a pilot is on a contact flight and any weather condition (ceiling, visibility, and so on) becomes less than the prescribed minimum, the pilot is required to proceed in a direction which will permit of flight under contact-flight rules or, if that is impossible, to land at the nearest airport.

Table 22 presents the contact-flight weather minimums in concise form for ease of comparison and memorization.

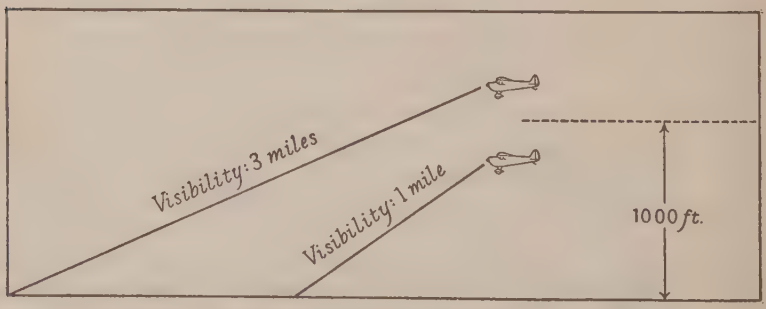


FIG. 337. Visibility minimums outside a control zone.

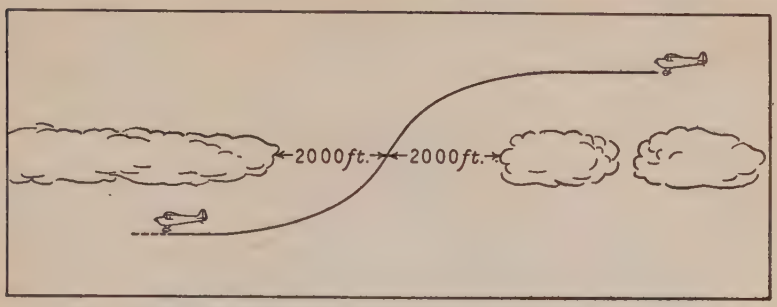


FIG. 338. Minimum horizontal distance from cloud layer.

TABLE 22

WEATHER MINIMUMS

	DAY	NIGHT
Ceiling		
No precipitation	800 feet	1000 feet
Precipitation	1000 feet	1000 feet
Distance above or below overcast		
No precipitation	300 feet	500 feet
Precipitation	500 feet	500 feet
Visibility		
In control zone		
General	3 miles	3 miles
At decision of control-tower operator	1 mile	2 miles
Outside control zone		
Above 1000 feet	3 miles	3 miles
Below 1000 feet	1 mile	2 miles
Horizontal distance from clouds	2000 feet	
Over the top	No flight	

Although you must know the minimums for contact flight given in this chapter, you should not consider these as necessarily safe for you. When flying cross-country it is well to have at least five miles visibility — better ten miles.

Questions

1. What are the rules regarding pilot certificates and aircraft certificates?
2. What are the rules regarding the method of taking off and landing?
3. What is the rule regarding the running of airplane motors?
4. If you have shut off the engine and wish to resume flight, what must you do to start the engine?
5. What is the rule regarding right of way of aircraft?
6. What is the minimum safe altitude (*a*) for flying directly over an airport, (*b*) for the completion of all acrobatics, (*c*) for flying over congested areas in cities, (*d*) for flying over land, (*e*) for the flight of seaplanes over open water in daylight?
7. What things may be dropped from an airplane?
8. What is the rule regarding the carrying of explosives and firearms?
9. What is the rule regarding the carrying of intoxicated persons?
10. What are the rules regarding acrobatic flights?
11. What are the rules regarding the use of parachutes?
12. Explain how a parachute is used.
13. What are the rules regarding night flying?
14. What is a civil airway?
15. What is a control airport?
16. What is the minimum height of ceiling under which flight may be made without instruments (*a*) in the daytime, (*b*) at night, (*c*) with precipitation?
17. At what distance above or below a cloud layer must a pilot fly (*a*) in the daytime, (*b*) at night, (*c*) with precipitation?
18. What is the minimum visibility under which ordinary flight may be made and what exceptions are there to the rule?
19. What horizontal distance must a pilot keep from clouds?
20. Under what conditions may a pilot fly without instruments above a layer of clouds?

44

CROSS-COUNTRY FLYING

THERE is a great deal of enjoyment to be gained in learning to fly a plane and in the feeling of growth and mastery that comes with the acquisition of skill in the various maneuvers necessary to obtain the private pilot rating and in the confidence one has in a modern plane. But a new thrill is had when the pilot sets out on a cross-country trip.

Planning the trip

Let us suppose that as our first cross-country trip we decide to fly from the city of New York to Richmond, Virginia, and return. The first step is to plan the route, in order to know where we may stop to rest or get gasoline.

We need one or more aviation charts. Consulting the index to the sectional aeronautical charts (Fig. 169, page 288), we find that we need the charts entitled New York, Washington, and Norfolk.

Choice of method of avigation

We must decide whether to avigate by pilotage, following highways, railroads, and other landmarks; by dead reckoning; or by radio avigation. This being our first cross-country trip, we decide to rely principally on pilotage in order to feel secure in knowing exactly where we are at all times. We are provided with a compass and a radio for use when necessary or desirable.

On consulting the chart we find that there is a double-track railroad from New York to Richmond, and we decide to follow this, at least on the first part of the trip.

We decide to stop at Philadelphia and again at Washington, to get gasoline and to rest and stretch a little.

Airport directory

It is well to learn in advance whether there are any special regulations regarding landing at these airports. The Civil Aeronautics Authority has compiled a Directory of Airports and Seaplane Bases. The directory is divided into seven parts, each published in a separate booklet and dealing with one of seven regions of the United States. The booklets may be obtained for 10 cents each from the Superintendent of Documents, Washington, D. C.

Consulting the directory that pertains to Region No. 1, we find that we would not be permitted to land at the Municipal Airport in Washington unless we had a radio receiver; otherwise we could land at an auxiliary field at College Park, Maryland.

Portable radio

However, we are equipped with a radio receiver — a portable radio operating from batteries good for 200 hours; with self-contained antennae; with two dials, one for standard frequencies (ordinary music broadcasting) and one for reception of aviation broadcasting. The radio has a loudspeaker; also it is equipped with earphones, which are advisable.

We may land therefore at the Washington airport.

Emergency fields

Some airports shown on the charts are only emergency fields — without hangars, without repair service, sometimes without gasoline, or perhaps with gasoline furnished only in 5-gallon cans — listed in the directory as "emergency fuel."

In the East, where good-sized cities are fairly close together, one is never far from a good airport with service. But out West it is essential to know the facilities at an airport before planning to stop for gasoline, service, or storage. On a trip to California in a light plane one of the writers of this book was once obliged to carry a 5-gallon can of gasoline in addition to the supply in an auxiliary tank, and to stop at an airport marked on the map but completely deserted, and pour the gasoline from the can into the tank, in order to get to the next airport that had fuel. The deserted airport was shown in the directory as having "fuel from town." It is best to look in the directory and then play safe.

Folding the charts

Since our charts are too large to consult spread out in the cockpit, it is well to have them properly folded in advance for easy reference. The best way to fold a chart for quick reference is the accordion fold. First fold the chart across the middle lengthwise, with the blank side inside; then fold it in six (or eight) accordion folds, as shown in Figure 339. The chart then opens like a book at any part, either top or bottom.

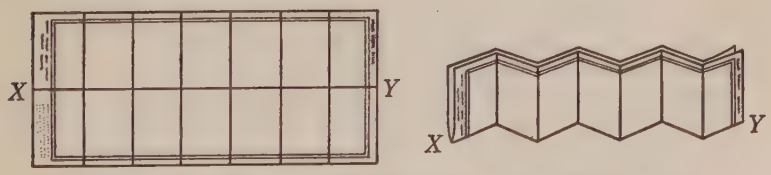


FIG. 339. The proper folding of an aeronautical chart.

Marking charts

Before starting on our trip it is well to mark up our chart, or charts, for convenience in checking our location as we progress. Let us say we expect to fly at about 80 miles an hour.

We find that along the railroad every 5-mile point is indicated on our chart by a cross line or lines, as shown in Figure 340. We know that at 80 miles an hour we shall pass the cross marks at intervals of 4 minutes. Thus we see that after leaving Newark we may expect to get to Rahway in 8 minutes, to New Brunswick in 18 minutes, to Monmouth Junction in 25 minutes, and to arrive at the edge of Trenton in about 38 minutes. We write these numbers opposite the towns on the chart. It is well to have an extra watch hung

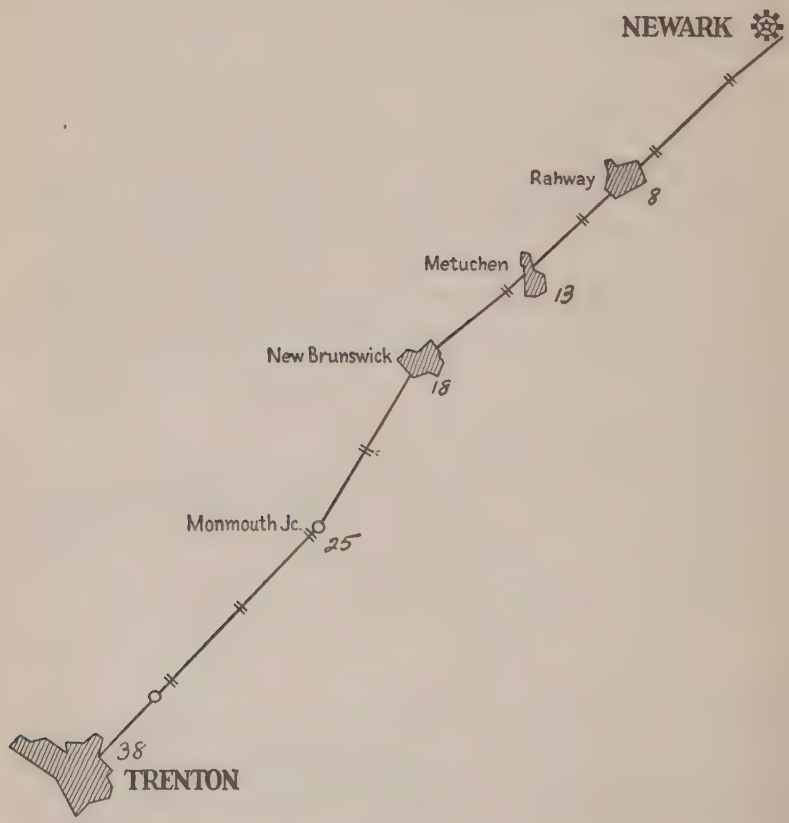


FIG. 340. The expected time of arrival marked at points on a chart.

on the panel of the plane, and after taking off and circling the field to set this at 12 : 00. Then as we pass each town on the trip we check it off on the chart and note whether or not we are keeping to schedule. This helps us to keep track of our location at all times and to avoid getting lost. Also it reduces to a minimum any figuring necessary while flying.

Check everything before the take-off

Before taking off for a trip we will look the plane over carefully to see that everything is in order and that the controls function properly.

Before entering the plane we will see that it is properly supplied with gasoline and oil.

While the engine is warming up, we need to consider the following questions:

(1) Do we have the necessary charts folded ready for immediate use as needed?

(2) Is the extra watch ready?

(3) Is all baggage and equipment, as stakes, rope, and parachute, in the plane?

(4) How about gas and oil? Give them one more thought.

(5) Have we learned about the weather ahead, including winds aloft?

(6) Have we filed a flight plan (page 611)?

(7) Do we know the wind direction for the take-off?

(8) Is the safety belt fastened?

Preparing for emergency landing

It is a saying that "every pilot will have at least one forced landing in his lifetime." The wise pilot, flying with one engine, remembers the remote chance that the engine may stop; and he is always on the lookout for a safe place in which to set the plane down. The cautious pilot "flies from farm to farm," so to speak, always keeping in sight of some possible

landing field. "It is better to be an old pilot than a bold one" is another aviators' saying.

In our trip from New York to Richmond we can fly at 3000 feet and always be within safe gliding distance of a field large enough to set the plane down in in an emergency.

Keeping track of wind direction

Of course we should know at all times which way the wind is blowing and in what direction we should undertake to land in case of emergency. The direction of the wind can be determined by noting —

(1) the direction of smoke,

(2) the movement below us of the shadows of clouds,

(3) the direction of streaks on lakes and other bodies of water, and

(4) the motion of trees, standing grain, and flags.

Landing at Philadelphia

As we approach Philadelphia airport, we take a good look around to be sure not to fly close to any other aircraft. We circle the airport to the left and note the direction of the wind sock and also the direction of traffic — the take-offs and landings of other planes. If for any reason the traffic is not in the direction of the wind sock, we may choose between landing in the direction of the traffic or in the direction indicated by the sock. If the wind is light, it is preferable to disregard the sock and land in the direction of the traffic. If the wind is strong, it is probable that it has just changed its direction and we should land in the direction indicated by the sock, taking care not to interfere with planes that have just landed in a different direction. Our new direction of landing establishes a new direction of traffic which those landing after us will take account of, if they see us, in deciding in which direction they will land.

Stopping at Philadelphia, we may as well fill up the tank. It never does any harm to have more gasoline than is needed for the next hop. So while still in the air we note where the gasoline pit is and after landing pull up to it. The attendant approaches with a smile and says, "Gas her up?"

The next hop we have planned is to Washington (140 miles). We decide in the interest of safety to *file a flight plan.*

Filing a flight plan

The Civil Aeronautics Board makes provision to safeguard private flying by furnishing check-up service free of charge. That is, if we notify the C.A.A. operator at Philadelphia that we propose to fly to Washington, he will notify the Washington operator of that fact by radio or teletype; then the Washington operator will be on the lookout for us, and if we do not arrive within a reasonable time he will take steps to have us found.

To file a flight plan, we give the C.A.A. operator the necessary information about our trip — airplane license number, our name, name of plane, air speed, destination, proposed time of departure and of arrival at destination, whether or not we have a radio, and so on.

This information is put on the teletype machine and transmitted to the control tower of the Washington airport.

With farms close together along the route and with telephones in many farmhouses, it is not likely that we would be left stranded in case of a forced landing in a field. That is, between cities along the North Atlantic a flight plan is not as necessary as out West. For example, in flying from Los Angeles to Yuma, Arizona, we cross 50 miles or more of hot desert without seeing a habitation, and that would be a long way to walk! In that part of the country we are careful to file a flight plan, take on board a plentiful supply of water, and hope that in case of a forced landing the C.A.A. will act promptly.

We must be careful on arriving at our destination to check in; otherwise the C.A.A. will begin telephoning to intermediate points to check on our whereabouts, and we may very properly be called upon to pay for these messages.

On arriving at Washington we find that we have a few minutes to spare before the "expected time of arrival" in our flight plan; so we circle the city at 3000 feet and take a look at the Capitol, the White House, the Mall, the Washington Monument, the Lincoln Memorial, the large government buildings, the diagonal avenues, the Potomac, and the Amphitheater at Arlington.

As we circle the airport, we listen in on the Washington frequency (278 kilocycles) and a voice says "Aeronca NC 22307, if you hear me, dip your wings." We move the ailerons and rock the plane back and forth a little. The voice then says, "OK, Aeronca NC 22307, land on the southwest runway."

The frequency 278 is the standard control-tower frequency, the same for the various airports; it is not to be confused with the radio range frequencies.

Flying by compass

The highway from Washington to Richmond is a little off from a straight line, as shown in Figure 341; hence in order to save time we decide to try flying direct to the Richard E. Byrd airport at Richmond by compass — dead reckoning.

Finding the true course

First, to find in what direction the Richard E. Byrd airport lies from the Washington airport, we draw a line on our chart, joining these two airports. We find a *compass rose* near Washington on the map, and by drawing a line through the center of the compass rose parallel to our line joining the airports, we find that the Richmond airport is in the direction 189°, or 9° west of south, from Washington.

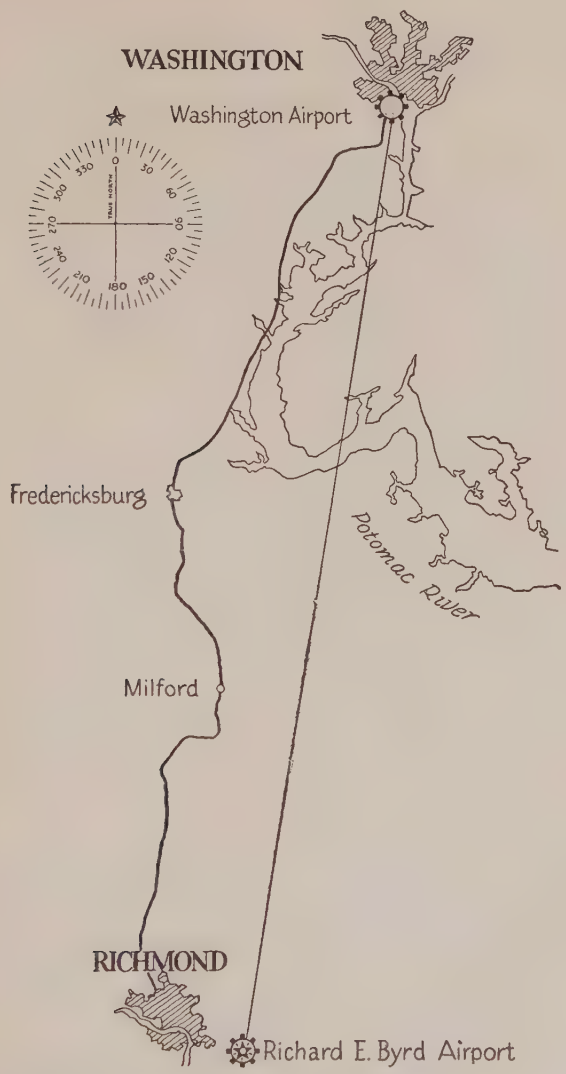


FIG. 341. Flying by dead reckoning from Washington to Richmond.

Finding the true heading

On the wall of the Weather Bureau office at Washington we find the latest report of winds aloft to read:

WA09 01109 1015 20918 0820 40725

This shows that at 3000 feet, our cruising altitude, the wind at 9 o'clock was from 80° at 20 miles a hour (page 560), with no more favorable condition higher up. Solving the wind-correction triangle based upon the true course, we find our *true heading* (page 322) to be 201°. We need to correct this for variation to find the *magnetic heading*, and for deviation to find the *compass heading*.

Finding the magnetic heading

Our route crosses a red line on the chart indicating a variation of 6° west, showing that in this locality the compass will read 6° more than the true angle from north; that is, the magnetic north is 6° west of north. Hence, remembering the rule "add west to true," we must add 6° to 201° to find the magnetic heading, the direction in which to head the plane in order to fly directly toward the destination, assuming that the compass is correct. The magnetic heading is 207°.

Finding the compass heading

Let us say our compass deviation card shows that for a magnetic course or heading of 207° the deviation of the compass is 3° E. The compass heading is therefore 207° − 3°, or 204°. We must steer the plane with the compass at 204°.

If our computation is made in the manner shown in Chapter 22, it will appear as follows:

T	V	M	D	C
201	6 W	207	3 E	204

In this case the directions are headings, not courses.

Allowing for a wind of unknown velocity

If at any time we have neglected to inquire about the wind, or if no wind information is available, we can allow for the wind after departing.

You have already learned how to find a wind vector while flying; but it is not often convenient to solve a wind-correction triangle while in flight.

One simple way to correct roughly for a wind of unknown velocity is as follows:

(1) Find the compass course. (In this case it is $189° + 6° - 3° = 192°$.)

(2) Point the plane in the direction of the compass course (192°). Be sure that the compass has ceased swinging.

(3) Pick out a landmark straight ahead, as a mountain, hill, town, or lake. Do not choose a cloud!

(4) Disregard the compass and fly to the landmark. Let the plane point to one side if necessary.

(5) On approaching the landmark, repeat the process with reference to another landmark.

Radio avigation

Let us say that since we have a radio receiver we decide to use it to "fly the beam" on the return trip from Richmond to Washington.

The chart shows radio-range signals emanating from the stations near the Washington and Richmond airports (Fig. 342). We note that the Richmond radio station operates on a frequency of 260 kilocycles with identification letters RW (· — · · — —).

So we start from the Richmond airport and fly in the general direction of Washington. (Since the direction of Richmond from Washington was 189°, the opposite direction is $189° - 180°$, or 9°.) We put on the earphones, turn on the radio, set the dial pointer at 260, and listen for the signal.

We note whether the signal is an N signal (— ·) or an A signal (· —) or the on-course signal — continuous tone. We check to see that the identification signals as given each half minute are "dit, dah, dit; dit, dah, dah" for "RW," Richmond.

If we hear the N signal, we know we are in the N quadrant (to the left of the course); so we veer to the right until we get the on-course signal.

If we hear the A signal, or if after getting the N signal we pass through the on-course signal to the A signal, we know we are in the A quadrant; and we veer to the left until we get the on-course signal and try to stay on this course or slightly to the right of it.

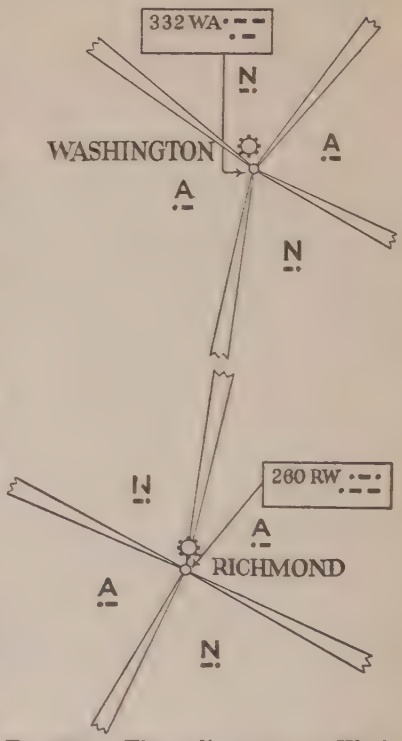


Fig. 342. The radio ranges at Washington and Richmond.

Checking on landmarks

While flying by compass or beam we check our location as often as possible by reference to landmarks.

For example, there are two towns, Duane and Sparta, directly on the beam as shown on the chart (Fig. 343), each on a prominent highway. These and the Rappahannock River serve as landmarks. By scale measurement on the chart we are due to arrive at Duane in 20 minutes, at Sparta

in 27 minutes, and at the river in 36 minutes. We note these times on the chart, as shown. When we have flown nearly 20 minutes we must be on the lookout for a town and note the exact time we pass it, and the same again for 27 minutes. We need not be so careful about the towns in this particular case because the prominent river will be a very definite check when we reach it, and we can see it far off. When the river is reached, we must check up carefully and see whether we are on schedule. Suppose we find that we have arrived at the river at 42 minutes past the starting time. We were due in 38 minutes; hence we have lost 4 minutes, or about 1 minute in 10. We assumed at the outset that we would arrive at Washington in 90 minutes; but at our present rate we must add 9 minutes for an adverse wind, and plan to arrive at Washington in about 99 minutes.

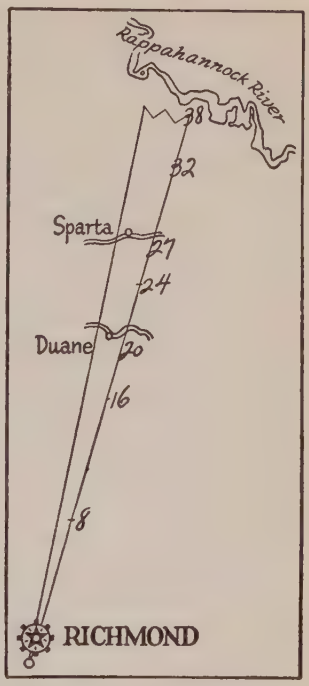


FIG. 343. A chart marked with expected times of arrival at points along a beam.

When we get to the halfway point between airports and note that the Richmond signals are getting a trifle faint, we move the pointer to 332 (Washington frequency; Fig. 342) and pick up the Washington signals.

Hereafter the N signal means that we are to the right of the course, and the A signal means that we are to the left of the course (the reverse of the Richmond signals).

Obviously by following this beam we are led directly to the Washington radio station, from which we can see the airport (Fig. 342).

After a brief rest and refueling at Washington, we decide to pass up Philadelphia and fly right through to New York. We pull out to the runway and wait for the green light in the control tower. On getting the green light, we take off, feeling quite nonchalant. In a moment we hear a loud flapping. What can be the matter? We find we forgot to fasten the safety belt and left it hanging outside the door. The buckle has nearly punched a hole in the fabric!

To our surprise, by the time we approach Baltimore the sky to the north has begun to get dark. Then we realize that we neglected to ask at Washington about the weather ahead. The weather had been so good from Richmond to Washington that we must have thought that it would always be good.

The darkness seems to extend clear down to the ground. No telling what the weather will be even at Philadelphia by the time we get there! We decide to land at Baltimore.

After we have taxied up to the office and shut off the engine, a voice on the loud-speaker bids us push the plane over to the hangar, as an airliner is due to arrive in a moment. This we can do without help, as one person can easily push a light plane.

The weather office at Baltimore reports showers to the north. Just as well that we landed!

We put in an hour studying charts and other information on the wall in the weather office and then we get a report that it is all clear ahead.

We have little to worry about, finding our way to New York (Fig. 344). We can follow Chesapeake Bay to its end, then fly eastward a short distance to the tip of Delaware Bay. Next we have merely to follow the Delaware River to Philadelphia and right on up to Trenton, around the bend. From Trenton we could hardly miss Staten Island, only 35 miles to the northeast. Being familiar with the metropolitan area, we need only head in a general northeast direction and in half an hour we can see New York City.

FIG. 344. Map showing part of our Middle Atlantic coast area.

Flying to Florida

Our first trip was a short one. Perhaps our next one will be a trip to Florida. There is a double-track railroad all the way from New York to Jacksonville, which we can follow if we wish to rely principally on pilotage.

From Richmond the double track goes by way of Rocky Mount, North Carolina; Florence, South Carolina; Charleston, South Carolina; and Savannah, Georgia, to Jacksonville, Florida. We can then follow the coast line if we wish to go to Daytona Beach and Miami.

You will find air travel in some of the Southwestern states especially pleasurable, partly because there is less haze and partly because of the safety. In flying west from Amarillo, Texas, for example, the countryside is just one large landing field. For 40 miles one can fly at 500 feet and at any moment drop down to a smooth landing.

Flying by railroad and highway is very easy in the West, where sometimes only one railroad with an accompanying motor highway can be seen for miles, and that quite straight. But in the more densely populated states of the Midwest and East there are so many railroads and highways cross-crossing that one can hardly rely on pilotage alone.

Storms

Although a great deal of weather information is available to the airman, it sometimes happens that bad weather is encountered which could not be foreseen.

As we have said, any plane can outfly any storm. That is, if you see a storm coming your way and can fly in the opposite direction it can never overtake you. Storms seldom travel 30 miles an hour.

But if you are flying, say from Tampa to Palm Beach, Florida, and see a storm coming, you cannot very well head out over the Everglades! A storm may approach from the side and sometimes cannot be avoided.

It is possible to fly through a small rainstorm. Or you can fly around a small storm without going far out of the way.

But if a widespread storm approaches and it is possible to set the plane down, this may be the wise thing to do. In such a case the pilot must be prepared for a strong wind, at least for a brief time.

As explained previously, a plane is easily blown away in a strong wind and must be staked down in order to be held. It is advisable, therefore, always to be supplied with stakes and rope on an extended trip.

Remember that to stake a plane down we try to have it face away from the wind, so that the wind blowing against the slanting tail and wing surfaces will tend to hold the plane down. Three stakes should be driven and ropes tied, one to each wing strut and one to the tail.

Emergency landings

Occasionally, in order to avoid flying through a storm or for other reasons, it is necessary to set the plane down in a fairly small field. The field may be bounded by trees and it may be difficult to get the plane into the field and stop it before it reaches the trees on the far side.

When landing the plane in such a case, it is wise to shut off the ignition just when about to land, so that if trees or other obstacles are struck there will be less likelihood of fire.

When taking off in a small space, be sure to take out all baggage and all extra weight of every kind, even sacrificing fuel if necessary, to make the plane as light as possible. Also remember that it is possible to take off in much less space in a strong wind than in a gentle one or in no wind. To be safest, wait for a strong wind.

Cross-country flying

There is no reason for a pilot to hesitate to take a trip of any length, provided —

(1) the plane is in perfect condition at the start;

(2) the plane is inspected frequently on the trip in order to discover any trouble before it can result in damage;

(3) no hop is begun unless the weather ahead is ascertained and known to be good; and

(4) the pilot flies high enough to be within safe landing distance of a field at all times.

Crack-ups

A pilot frequently hears about "crack-ups" and will occasionally see a cracked-up plane in the corner of a hangar visited.

It will usually develop that the crack-up was the pilot's fault, for one of the following reasons:

(1) he did not inspect the plane before taking off;

(2) he forgot to check the gas and oil;

(3) he did not warm up the engine sufficiently;

(4) he tried to climb too steeply, or to make too sharp a turn near the ground;

(5) he did not check the weather ahead, and took a chance later on flying through a storm;

(6) he let clouds close in below him;

(7) he did not take precautions against the plane's blowing away in the wind on the ground;

(8) he tried to land cross-wind in too strong a wind;

(9) he tried to land on a soft beach or other place not known to be suitable for landing;

(10) he attempted to land at an airport without scanning the sky for other aircraft, or without seeing that the field was clear;

(11) he did not take good care of the engine — let the valves lose compression, the points get pitted, the spark plugs get burnt;

(12) he was doing acrobatics too near the ground and stalled;

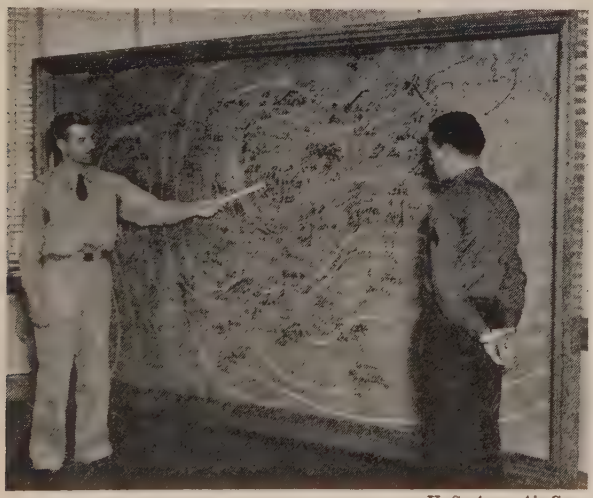
(13) he was out shooting coyotes and flew along too near the ground; or

(14) he went to sleep at the switch!

Questions

1. What considerations determine the choice between pilotage, dead reckoning, and radio avigation in cross-country flying?
2. Of what use is an airport directory to a pilot?
3. Is it possible to use a portable radio in an airplane?
4. How is a chart folded for most convenient reference?
5. How may a chart be marked for convenience of the pilot in checking his location before embarking on a trip?
6. In what way does a pilot prepare for an emergency landing?
7. What ways can you name for keeping track of wind directions?

8. What is meant by filing a flight plan?
9. Must a pilot file a flight plan whenever he embarks on a trip?
10. What devices may be used to allow for a wind of unknown velocity?
11. Under what circumstances might an airplane be in danger of being blown over?
12. What precautions may a pilot take against having a plane blown over?
13. What precautions may a pilot take against fire in case of a forced landing?
14. What precautions should a pilot take when necessary to fly a plane out of a small field?
15. What are some of the causes listed for crack-ups of airplanes?



U. S. Army Air Corps

FIG. 345. Meteorological instruction being imparted in the Army Flying School at Randolph Field, Texas. Instruction in the science of meteorology is given by several of our great universities, by the United States Weather Bureau, the Army, the Navy, and the airlines.

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RESEARCH AND TRAINING

THE United States Government is undertaking a very thorough program of research in aeronautics in order to improve and safeguard flying; also a program of training fliers, largely in the interest of national defense.

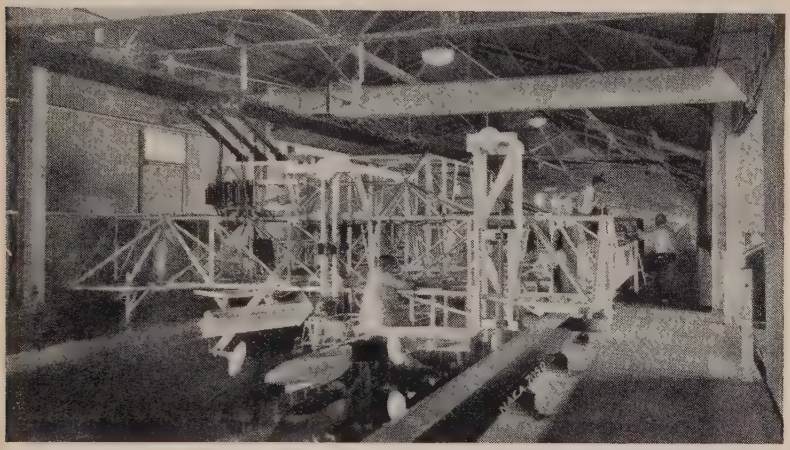
National Advisory Committee for Aeronautics

In order to promote aviation in all its aspects there was created by an Act of Congress in 1915 a National Advisory Committee for Aeronautics, often referred to as the N.A.C.A. Its purpose was "the supervision and direction of the scientific study of the problems of flight." Members are appointed by the President and serve without compensation.

The Committee publishes an annual report consisting of a group of scientific reports by various authors, dealing mostly with the research conducted during the year. The volume for 1939 was the Twenty-Fifth Annual Report and contained Reports Nos. 645 to 680. Typical titles are: *The Aerodynamic Characteristics of Six Full-Scale Propellers Having Different Airfoil Sections* (No. 650), and *Downwash and Wake behind Plain and Flapped Airfoils* (No. 651).

Research laboratories

The National Advisory Committee for Aeronautics has maintained an important technical laboratory at Langley Field, Virginia, where many valuable researches have been conducted. A second major aeronautical research station, approved in 1939, is being built at Moffett Field, California, 38 miles south of San Francisco.



National Advisory Committee for Aeronautics

FIG. 346. N.A.C.A. tank at Langley Field, Virginia. The white structure is the towing carriage which runs on the rails at either side of the tank. A model of the hull of a flying boat is shown mounted ready for a test in the tank. The towing carriage has a run of 2800 feet and a maximum speed of 80 miles an hour.

Technical committees

For the stated purpose of carrying out more effectively its principal function of the supervision, conduct, and coördination of the scientific study of the problems of aeronautics, the N.A.C.A. has established a group of technical committees which prepare and recommend to the main committee programs of research in their respective fields.

There are four principal technical committees — one on Aerodynamics, one on Power Plants for Aircraft, one on Aircraft Materials, and one on Aircraft Structures. The Committee on Aerodynamics is studying, among other things, landing speed and landing range, control and controllability, stability and maneuverability, stalling and spinning, take-offs and landings, airfoils, propellers, ice formation and its prevention. Equally important topics are studied by the other committees.

Institute of the Aeronautical Sciences

The members of any profession feel the need of an organization to which they may belong, which will meet at regular intervals, enable the members to get better acquainted with each other, and — most important of all — provide an avenue for the interchange of ideas through publications and otherwise. To that end a number of aeronautical specialists organized the Institute of the Aeronautical Sciences in 1932, and it was incorporated under the membership corporation law of the State of New York.

The Institute is located at Rockefeller Center, New York City, and has over 3000 members.

Free lending-library service

It is important to know that the Institute maintains a free lending service from a library of many thousand aeronautical books, magazines, pamphlets, photographs, and reports, with the largest specialized aeronautical index in the world.

Any person in the United States over 18 years of age who can furnish satisfactory references concerning his responsibility and reliability can become a member of the library and borrow books without charge except for return postage. For further information address the Paul Kollsman Library, 1505 RCA Building West, 30 Rockefeller Plaza, New York City.

Army and navy pilot training; flying cadets

The Army Air Corps needs a large number of competent military pilots, and therefore maintains flying schools in various parts of the country where training is given to promising young men at government expense. The students are known as *flying cadets*. They are paid a salary while learning to fly.

The army flying schools are located where flying conditions are good, especially with reference to all-year-round flying weather.

The army conducts a nine months' course, divided into three parts, as follows:

Three months, elementary course;
three months, basic course; and
three months, advanced training.

The course covers flight training, avigation, aerodynamics, meteorology, radio, and still other subjects.

Classes start every six months. The first three months' training is given under the supervision of the army at civil flying schools, which are as follows:

Alabama Institute of Aeronautics, Tuscaloosa, Alabama;
Chicago School of Aeronautics, Glenview, Illinois;
Lincoln Airplane and Flying School, Lincoln, Nebraska;
Parks Air College, East St. Louis, Illinois;
Spartan School of Aeronautics, Tulsa, Oklahoma;
Dallas Aviation School and Air College, Dallas, Texas;
Grand Central Flying School, Glendale, California;
Ryan School of Aeronautics, Ltd., San Diego, California; and
Santa Monica School of Flying, Santa Monica, California.

On completion of the three months' training at the civil flying school, the flying cadet is transferred to Randolph Field, Texas, for the next three months' instruction; and those who graduate from Randolph Field are sent to Kelly Field, Texas, for the last three months' training. A portion of Randolph Field is shown in Figure 9, page 9.

The courses include in all about 315 hours in the air, during which the cadet receives instruction in all the maneuvers necessary for the efficient piloting of military aircraft and is also given academic instruction in specialized military subjects.

The pay is $75 a month plus $1 a day for rations, while undergoing training. The cadets are housed free in barracks and are furnished their uniforms and equipment by the army.

Candidates applying for appointment as flying cadets must

be unmarried male citizens of the United States between the ages of 20 and 27 years.

Navy flight training

The United States Navy trains its pilots at the United States Naval Air Station at Pensacola, Florida, located on the Gulf of Mexico. (See Fig. 350, page 642.)

The ground-school course at Pensacola comprises theoretical and practical instruction in power plants (engines), aircraft structures, gunnery, avigation, communication, photography, and aerology. (Aerology may be defined as the description and discussion of the free air as revealed by kites, balloons, airplanes, and clouds.)

The course at Pensacola takes about one year and requires for completion 325 hours of flying and a thorough grounding in theoretical phases of aeronautics.

Civilian pilot training

In addition to provision for the training of pilots for the army and navy, the United States Government has established a Civilian Pilot Training Program, which includes not only private and secondary courses for the training of new civilian pilots but also "refresher" courses for pilots who already hold active or inactive certificates. Provision is made also for qualifying pilots with the necessary aeronautical experience to become flight instructors.

Participants in these courses must be citizens of the United States and must pledge themselves to apply for flight duty in the military service of the United States when needed.

Training courses

The following training courses are offered:

Private course, college and non-college phases. 72 hours of ground instruction and 35 to 45 hours of flight training.

Secondary course, college and non-college phases. 126 hours of ground instruction and 40 to 50 hours of flight training.

Cross-country course. 40 hours of ground instruction and 40 hours of flight training.

Instrument course. 40 hours of flight training.

Student instructor course. Minimum of 35 hours of ground training and 30 hours of flight training.

Instructor refresher course. 20 to 25 hours of ground instruction and 20 hours of flight training.

Secondary instructor refresher course. 25 to 30 hours of flight training.

Commercial pilot refresher course. 20 to 25 hours of flight training.

Private pilot refresher course. 10 to 15 hours of flight training.

Solo and amateur pilot refresher course. 25 to 30 hours of flight training.

Various prerequisites are specified for these courses, including age limitations, previous experience and training, and physical fitness.

Applications for the courses may be obtained from the Department of Commerce, Civil Aeronautics Administration, Attention: Civil Pilot Training Service, Washington, D. C. For further details see Bulletin No. 345, Revised as of December 12, 1940, which may be had free on request of the Civil Aeronautics Administration, Washington, D. C.

Civil Aeronautics Journal

The Civil Aeronautics Authority publishes twice monthly a journal called the *Civil Aeronautics Journal.* Subscription is $1 a year; single copies are 5 cents. It is sold by the Superintendent of Documents, Government Printing Office, Washington, D. C. Among the topics treated in the *Journal* are: Air safety, private flying, air transportation, manu-

facturing and production, airways and airports, and official actions.

The quotations that follow are made from the January 1, 1941, number (Vol. 2, No. 1).

"The Civilian Pilot Training Program, largest mass-flight training program ever undertaken in the United States, in 1940 resulted in 25,168 youths receiving their private pilots' certificates, and at the end of the year another 'batch' of nearly 15,000 trainees was nearing completion of the preliminary flight course.

"Initiated on an experimental basis, with 330 students in 13 colleges, the C.P.T.P. extended under the Civilian Pilot Training Act of 1939 to a point where some 10,000 students were trained between July 1, 1939, and July 30, 1940, in more than 500 college and non-college centers throughout the entire country. Of this total, 8327 trainees in the preliminary college program completed instruction in the spring of 1940.

"Shortly thereafter Congress authorized funds for the training of about 45,000 youths in the year beginning July 1, 1940. That same month the first part of the program began. The preliminary college training took place at 495 centers, with 15,413 enrollees, of which there were 13,288 completions in the fall of the year. Participating in this phase of the program were 460 instructors, 530 flight operators, 1972 aircraft, and 435 airports."

Questions

1. Under what agencies is the United States Government training fliers?
2. What is the National Advisory Committee for Aeronautics?
3. What is the Institute of the Aeronautical Sciences?
4. What free lending-library service is available to pilots?
5. What are flying cadets?
6. What is the length of the course conducted by the army for pilots?
7. Where are the flying cadets trained by the army?
8. Where are pilots trained for the United States Navy?
9. What is the Civil Pilot Training Program?

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AVIATION — PAST AND FUTURE

ON December 17, 1903, Wilbur Wright and Orville Wright made the first flight in a heavier-than-air motor-driven plane at Kitty Hawk, North Carolina.

The first officially recorded flight was made in 1905 by Orville Wright, who flew 11.12 miles in 18 minutes, 9 seconds, the rate being 37 miles an hour.

Ten years after the first flight (1913), Daacort, a Frenchman, flew non-stop from Paris to Berlin — 542 miles; and Prévost, also a Frenchman, flew a plane at 126 miles an hour.

Twenty years after the first flight (1923), Kelly and McCready, Americans, flew non-stop from New York to San Diego, California, 2516 miles; and Williams, an American, flew a plane at 266 miles an hour.

Thirty years after the first flight (1933), Godos and Rossi, Frenchmen, flew non-stop from New York to Syria, 5900 miles; and Agello, an Italian, flew a plane at 423 miles an hour.

In 1938 Gromov, Yumachev, and Danilin, Russians, flew over the North Pole from Moscow to San Jacinto, California, 6296 miles; and Agello established a world's record by flying at 440 miles an hour.

The present automobile land speed record is held by Captain G. E. T. Eyston, 311.42 miles an hour. The present speedboat record is held by Sir Malcolm Campbell, 129.4 miles an hour.

In 1937 Adam, an Englishman, established an altitude flying record of 59,927 feet.

Aviation progress

In the "old days" engines were unreliable and forced landings were frequent. One pilot tells of having 17 forced landings in 100 hours; another tells of having 3 forced landings on a single trip!

Nowadays planes have reached such a high degree of effectiveness, dependability, and safety that the buyer now gives attention to the quality of upholstery and the shine of the fittings!

More private flying

According to figures made public recently by Donald H. Connolly, Administrator of Civil Aeronautics, the recent growth in the number of certificated pilots is as follows:

Jan. 1, 1938 — 17,681 certificated pilots.
Jan. 1, 1939 — 22,983 certificated pilots.
Jan. 1, 1940 — 31,264 certificated pilots.
Jan. 1, 1941 — 63,113 certificated pilots.

We see that during the year of 1940 the number more than doubled.

With mass production of small airplanes and the impetus given to flying by the demand of the Civil Aeronautics Authority for pilots for army duty, we may expect a great deal more private flying than there has been in the past.

Eventually, no doubt, we shall have effective amphibian planes, standardized and reasonable in price.

Increased safety

Preliminary figures indicate that the number of miles of flying by private pilots per fatal accident will be nearly 1,000,000 for 1940, as against 916,846 miles per fatal accident in 1939, 752,088 in 1938, and 557,818 in 1937. We might say that the safety of private flying has nearly doubled in three years.

Opportunity for improvement; folding or removable wings

Pending such time as we can take off and land from the roof or the back yard, we need planes with wings that either fold up or can be removed and placed in a rack in the hangar, the plane then being capable of being propelled on its own power on the highway, without use of the propeller. With such a plane we could start from our own garage, drive to the airport, put on the wings, fly to the airport of our destination, drop the wings, and drive to a friend's house. Some progress has been made in the direction of folding wings and "roadability," but there is still plenty for young inventors to think about!

Future size of airplanes

It is rumored that a new engine is being tested having 42 cylinders (six 7-cylinder radial engines combined) developing 4200 horsepower.

As you saw by Table 10, page 223, the Clipper ship, present largest flying boat, is much larger than the Stratoliner, present largest land plane. It seems that the next step in advance in airplane size will be the appearance of an enlarged land plane which is announced to be forthcoming in the immediate future. It is said to have these features:

1. Four 2500-horsepower engines.
2. A capacity of 64 passengers and crew of 7, or a cargo capacity of over 16 tons, net load.
3. A top speed of 350 miles an hour (100 miles faster than any other transport plane).
4. A range of over 4000 miles.
5. Supercharged cabin and engines, permitting operations up to 30,000 feet.
6. Twenty per cent reduction in cost of operations per seat mile or ton mile.

In this connection it is interesting to note the great improvement in engine construction that has occurred, especially in the reducing of the weight of engines per horsepower generated. Research leading to this improvement has been stimulated by the special need of relatively light engines for aircraft.

In the horse, characterized by Henry Ford as a "hay motor," we have 2000 pounds of weight to one horsepower. There has been no basic change in hay-motor design for a million years. Man-made engines of the latest types show the following relationships of weight to horsepower:

horse	2000 pounds per H.P.;
railroad engine	75 pounds per H.P.;
steamship engine	26 pounds per H.P.;
automobile engine	7 pounds per H.P.; and
aircraft engine	1.2 pounds per H.P.

The new liquid-cooled 12-cylinder engine being constructed for the United States Army is said to weigh 1325 pounds and deliver 1090 horsepower, thus weighing only about 1.2 pounds per horsepower (*Life*, January 13, 1941).

Increased use of seaplanes

Seaplanes of the two-float type are rapidly coming into more extensive use by private pilots because of their various advantages (see page 270), and because the earlier disadvantage of insufficient seaplane bases is being eliminated.

Having learned to fly a land plane, you can very quickly learn to fly a seaplane. The methods of taxiing land planes and seaplanes differ and there are slight differences in the methods of taking off and landing, which are easy to learn. In normal flying you will hardly detect a difference.

Taxiing a seaplane

An important thing to remember when learning to taxi a seaplane is that it is not resting on the ground but is

floating and being moved by the current. A conventional seaplane, floating free and idling, tends to turn like a weathervane to the position in which its nose points upwind. Then it will creep forward or drift backward, depending on the relative forces of thrust, wind, and water current. A seaplane has no brakes! Hence in approaching a dock, buoy, ramp, beach, or other craft, you must always anticipate this weathervaning and the current and allow for them.

This means, for example, that you must not expect to be able to taxi directly crosswind or cross current to a mooring place. To allow for weathervaning, you may need to approach the dock slightly to the leeward so that when you slow down and the plane weathervanes you will be a little downwind from the mooring place and can approach it upwind. Similarly, to allow for a current you may need to approach the dock a little upstream. You may need to combine the allowances for weathervaning and current.

Also you must learn by practice just when to close the throttle when approaching the mooring place, so that the seaplane will not be caught short and be turned sidewise to the point you wish to reach and so that you will not leave the power on too long and consequently bump.

Here is an important rule to remember in taxiing a seaplane under windy conditions. Never use power when turning from downwind to upwind; use power when turning from upwind to downwind. To turn the taxiing plane upwind, you have only to close the throttle and let the wind blow the tail around. If you apply power to turn upwind, the propeller blast on the rudder creates a sideward force which is added to the sideward force of the wind and tends to capsize the plane. Moreover, the float on the outside of the turn, being pressed more deeply into the water, slows the turning, thus calling for more blast on the rudder, which creates more sideward force, and increases the tendency to capsize the plane. On the other hand, in making a turn to

downwind you must use power to overcome the tendency to weathervane; but in this case the propeller blast on the rudder and the force of the wind act on opposite sides of the plane and tend to neutralize each other, thus lessening the danger of capsizing. When it becomes necessary to taxi downwind, keep the elevators and ailerons level and, except on rough water, taxi faster than the wind.

Take-offs and landings

The slight differences between seaplanes and land planes in take-offs and landings are quickly learned. Naturally, take-offs and landings are made upwind whenever possible. When resting on the water a seaplane is already level, and there is no pushing forward on the stick to lift the tail. Instead, you hold the stick fully back at the start in order to hold the floats bow up, to avoid spray on the propeller, and to lift the plane up "onto the step." (See Fig. 347.) As the plane gains speed the stick should be eased forward slightly while the floats are riding "on the step." Then, as with a land plane, you finally "lift the plane into the air" by a slight pulling back on the stick.

Fig. 347. A seaplane float taxiing "on the step."

Ordinarily a seaplane is landed in the same way as a land plane. Glide down and level off slightly above the water, and, as with a land plane, hold the seaplane above the surface while you gradually lower the tail as you lose flying speed. Hold the stick back during and after the landing.

You will learn that the apparent distance you are above glassy water is very deceptive. In attempting a normal landing on glassy water you may strike it before you have leveled off. To avoid this possibility, land close to the shore or a boat or buoy which will indicate the water level; otherwise, level off well above the surface, keep about half power on, and come down and land nose high.

In landing with wind blowing, remember that the waves are moving downwind. The motion of the waves with reference to the foam shows the direction of the wind. The motion of the waves may make you think your air speed is greater than it is.

If there is no wind and you are taking off from or landing on water that has an appreciable current, *take off down the current but land up the current.* Remember that for a given air speed your speed with reference to the water is less down the current than up the current. This reduces the drag of the water on the floats during the take-off. On the other hand, by landing up the current, the additional drag of the water on the floats slows the plane more quickly. There is no danger in this, assuming the water to be fairly smooth.

Do not get the impression that it is necessary to learn to fly a land plane before learning to fly a seaplane. With plenty of open water various disadvantages of a land plane are avoided, such as danger that may result from motor failure after the take-off, the necessity for circling the field after each take-off before landing, the danger of over- and undershooting, wheel landings, ground loops, noseovers, and heavy traffic at the airport.

Limitations of fixed-wing aircraft

With a conventional plane needing a quarter of a mile of runway in the direction of the wind merely to get into the air, and with airports already becoming crowded while the ratio of planes flown to automobiles driven is yet only one to several hundred, it is obvious that the limitations of the conventional or fixed-wing type of airplane are such that it will never serve as a general mode of travel comparable with the automobile.

In most cases one must drive an appreciable distance to the airport to get one's plane, and when arriving at another airport, must drive another appreciable distance to reach the

actual destination. This consideration alone prevents the present conventional type of airplane from serving as a means of travel for most ordinary purposes.

Qualities needed

Foremost among characteristics to be desired in a general-utility aircraft would be the ability to take off from practically a standstill, as from a small yard near one's home, and to land comparably in a small yard or on a parking lot within walking distance of one's destination.

Also it would be important in such a general-utility aircraft for one to be able to reduce its forward speed to 10 or 5 miles an hour — preferably to no forward speed — in the interest of safety. A capacity for slow forward motion would be necessary in order to avoid collisions in the congested traffic that would exist when aircraft came to be more generally used, and also in order to allow the aircraft to proceed cautiously in bad weather. Most of the danger of fog will be eliminated when aircraft can proceed very slowly and, if necessary, land in any convenient open space.

Rotating-wing aircraft; convenience and safety

Up to the present it has not seemed possible for fixed-wing aircraft to be given the capabilities of vertical ascent and slow forward speed needed for convenience and safety. But it has been found entirely possible to invest rotating-wing aircraft with these qualities. Recent demonstrations of autogiros and helicopters indicate that rotating-wing aircraft may help greatly in solving the problem of airport congestion, not only by providing the convenience of taking off from and landing on a small open space but also by providing the safety of slow forward speed necessary in congested traffic.

Intensive research in the field of rotating-wing aircraft is being conducted by various agencies, particularly by the United States Army Air Corps at Wright Field, Dayton,

Ohio; by the Pitcairn Autogiro Corporation; and by the National Advisory Committee for Aeronautics.

Recent demonstrations of the United States Army Air Corps showed a helicopter capable of taking off from a yard covered with two feet of snow.

The Whirl Wing autogiro

The Pitcairn Autogiro Company has recently developed a new autogiro called the Whirl Wing, which is capable of a "jump take-off." (See Fig. 348.)

The autogiro has no wings and is sustained by a three-bladed rotor to which power is applied for the take-off and which rotates of itself in level flight. Forward motion is attained by means of a four-bladed propeller situated as usual in the front of the plane.

Under normal conditions the autogiro will take off vertically to a height of from 15 to 35 feet, depending upon the amount of wind, and then swing directly into horizontal or climbing flight.

It can be driven on the ground by means of a power drive to the rear wheel — a large tail wheel. Steering is accomplished by a castering (steering) of the two main landing wheels controlled by the pilot's foot pedals. With the rotor blades folded back over the fuselage and a clutch between the engine and propeller disengaged, the plane can be driven along the road, like a car, to and from the hangar or garage.

The Whirl Wing can descend vertically until close to the ground and then land with a forward roll of but a few feet. In a light wind landings can be made with no forward motion at all. Descent can be halted and the plane brought back into a climbing flight.

The jump take-off is accomplished by setting the rotor blades at zero pitch, with full throttle speeding the rotor to about 300 r.p.m. The pitch of the rotor blades is then made

Pitcairn Autogiro Company

FIG. 348. The Whirl Wing Autogiro making a jump take-off over a hurdle. The broken line indicates the course of the plane in this take-off.

positive, and the momentum of the blades lifts the plane vertically.

The Whirl Wing is controlled in flight with the normal air plane hand wheel and foot pedals. The hand wheel controls the lateral and longitudinal movement of the rotor axis, and the pedals are connected to a vertical rudder on the tail.

The Sikorsky helicopter

A remarkable demonstration of maneuverability in aircraft has been made recently with the VS-300 helicopter as designed and flown by Igor I. Sikorsky, who merits the title dean of researchers in the field of rotating wing aircraft. This helicopter marks the culmination of forty years of study and experimentation by Sikorsky. (See Fig. 349.)

The VS-300 helicopter was shown to be capable of taking off straight up, flying level at 50 miles an hour, hovering (remaining motionless in the air), flying backward or sidewise, and landing straight down.

Controlling the helicopter

This helicopter has no fixed wings or fixed tail surfaces — no ailerons, elevator, or rudder. Sustention is effected by one large rotor of long slender blades with an axle approximately over the center of gravity. Two auxiliary rotors turning in a horizontal plane, one on each side of the tail, provide means for pitching and banking. The angle of

Vought-Sikorsky Aircraft

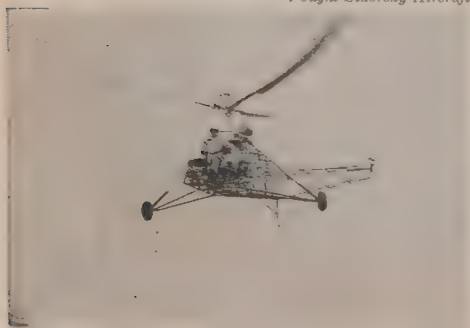

FIG. 349. The Sikorsky helicopter. There are a number of types of helicopters, all in the experimental stage.

attack of the blades of these auxiliary rotors may be altered from positive to negative and vice versa. When operating together with positive angle of attack they lift the tail, pitching the nose down. When operating together with negative angle of attack they depress the tail, thus pitching the nose up. When operating oppositely, one with positive and one with negative angle of attack, the helicopter is rolled into a banked position, or restored to level from a banked position.

Yawing is accomplished by means of a small third auxiliary rotor turning in a vertical plane on a lateral axis. This small rotor also is a reversible pitch propeller and can swing the tail to the left or right. It serves a second useful purpose; namely, to counteract the tendency of the helicopter to rotate in the direction opposite that of the main rotating wings.

As a forceful demonstration of the very sensitive maneuverability of the helicopter, it was brought down to within a few feet of the ground and held hovering in the air. An assistant standing on the ground laid a suitcase on the frame of the helicopter, whereupon the helicopter was caused to rise and fly away.

Promise of the future

The obstacles that have been overcome and that are yet to be overcome to achieve hovering and vertical take-off and landing appear to be far greater than the difficulties — of other character, now largely overcome — relating to conventional fixed-wing aircraft; but there is every reason to believe that the remaining obstacles are not insurmountable and that the rising generation will rise vertically in rotating-wing aircraft!

Questions

1. What two men made the first flight in a heavier-than-air motor-driven plane? Where and when was this flight made?
2. Can you mention any of the distance, speed, or altitude records that have been made, and by whom?

3. What is the world's record for speed in a plane? in an automobile? in a boat? What is the altitude record?
4. What are the relative weights per horsepower in the case of (*a*) a horse, (*b*) a railroad engine, (*c*) a steamship engine, (*d*) an automobile engine, and (*e*) an aircraft engine?
5. Explain weathervaning by a seaplane.
6. What differences are there between a seaplane and a land plane as to taxiing? as to take-offs? as to landings?
7. What are some of the limitations of the fixed-wing aircraft?
8. What qualities in an aircraft are needed to overcome these limitations?
9. In what way does rotating-wing aircraft afford convenience?
10. In what ways do rotating-wing aircrafts afford safety (*a*) in traffic? (*b*) in inclement weather?
11. What are some of the characteristics of the Pitcairn Whirl Wing autogiro?
12. What are some of the characteristics of the VS–300 helicopter as designed and flown by Sikorsky?

FIG. 350. A general view of the Naval Air Station at Pensacola, Florida, showing a line-up of basic training planes.

U. S. Navy Department

TABLE OF SQUARES AND SQUARE ROOTS

Num.	Square	Sq. Root	Num.	Square	Sq. Root	Num.	Square	Sq. Root
1	1	1.000	51	26 01	7.141	101	1 02 01	10.050
2	4	1.414	52	27 04	7.211	102	1 04 04	10.100
3	9	1.732	53	28 09	7.280	103	1 06 09	10.149
4	16	2.000	54	29 16	7.348	104	1 08 16	10.198
5	25	2.236	55	30 25	7.416	105	1 10 25	10.247
6	36	2.449	56	31 36	7.483	106	1 12 36	10.296
7	49	2.646	57	32 49	7.550	107	1 14 49	10.344
8	64	2.828	58	33 64	7.616	108	1 16 64	10.392
9	81	3.000	59	34 81	7.681	109	1 18 81	10.440
10	1 00	3.162	60	36 00	7.746	110	1 21 00	10.488
11	1 21	3.317	61	37 21	7.810	111	1 23 21	10.536
12	1 44	3.464	62	38 44	7.874	112	1 25 44	10.583
13	1 69	3.606	63	39 69	7.937	113	1 27 69	10.630
14	1 96	3.742	64	40 96	8.000	114	1 29 96	10.677
15	2 25	3.873	65	42 25	8.062	115	1 32 25	10.724
16	2 56	4.000	66	43 56	8.124	116	1 34 56	10.770
17	2 89	4.123	67	44 89	8.185	117	1 36 89	10.817
18	3 24	4.243	68	46 24	8.246	118	1 39 24	10.863
19	3 61	4.359	69	47 61	8.307	119	1 41 61	10.909
20	4 00	4.472	70	49 00	8.367	120	1 44 00	10.954
21	4 41	4.583	71	50 41	8.426	121	1 46 41	11.000
22	4 84	4.690	72	51 84	8.484	122	1 48 84	11.045
23	5 29	4.796	73	53 29	8.544	123	1 51 29	11.091
24	5 76	4.899	74	54 76	8.602	124	1 53 76	11.136
25	6 25	5.000	75	56 25	8.660	125	1 56 25	11.180
26	6 76	5.099	76	57 76	8.718	126	1 58 76	11.225
27	7 29	5.196	77	59 29	8.775	127	1 61 29	11.269
28	7 84	5.292	78	60 84	8.832	128	1 63 84	11.314
29	8 41	5.385	79	62 41	8.888	129	1 66 41	11.358
30	9 00	5.477	80	64 00	8.944	130	1 69 00	11.402
31	9 61	5.568	81	65 61	9.000	131	1 71 61	11.446
32	10 24	5.657	82	67 24	9.055	132	1 74 24	11.489
33	10 89	5.745	83	68 89	9.110	133	1 76 89	11.533
34	11 56	5.831	84	70 56	9.165	134	1 79 56	11.576
35	12 25	5.916	85	72 25	9.220	135	1 82 25	11.619
36	12 96	6.000	86	73 96	9.274	136	1 84 96	11.662
37	13 69	6.083	87	75 69	9.327	137	1 87 69	11.705
38	14 44	6.164	88	77 44	9.381	138	1 90 44	11.747
39	15 21	6.245	89	79 21	9.434	139	1 93 21	11.790
40	16 00	6.325	90	81 00	9.487	140	1 96 00	11.832
41	16 81	6.403	91	82 81	9.539	141	1 98 81	11.874
42	17 64	6.481	92	84 64	9.592	142	2 01 64	11.916
43	18 49	6.557	93	86 49	9.644	143	2 04 49	11.958
44	19 36	6.633	94	88 36	9.695	144	2 07 36	12.000
45	20 25	6.708	95	90 25	9.747	145	2 10 25	12.042
46	21 16	6.782	96	92 16	9.798	146	2 13 16	12.083
47	22 09	6.856	97	94 09	9.849	147	2 16 09	12.124
48	23 04	6.928	98	96 04	9.899	148	2 19 04	12.166
49	24 01	7.000	99	98 01	9.950	149	2 22 01	12.207
50	25 00	7.071	100	1 00 00	10.000	150	2 25 00	12.247

Num.	Square	Sq. Root	Num.	Square	Sq. Root	Num.	Square	Sq. Root
151	2 28 01	12.288	201	4 04 01	14.177	251	6 30 01	15.843
152	2 31 04	12.329	202	4 08 04	14.213	252	6 35 04	15.875
153	2 34 09	12.369	203	4 12 09	14.248	253	6 40 09	15.906
154	2 37 16	12.410	204	4 16 16	14.283	254	6 45 16	15.937
155	2 40 25	12.450	205	4 20 25	14.318	255	6 50 25	15.969
156	2 43 36	12.490	206	4 24 36	14.353	256	6 55 36	16.000
157	2 46 49	12.530	207	4 28 49	14.387	257	6 60 49	16.031
158	2 49 64	12.570	208	4 32 64	14.422	258	6 65 64	16.062
159	2 52 81	12.610	209	4 36 81	14.457	259	6 70 81	16.093
160	2 56 00	12.649	210	4 41 00	14.491	260	6 76 00	16.125
161	2 59 21	12.689	211	4 45 21	14.526	261	6 81 21	16.155
162	2 62 44	12.728	212	4 49 44	14.560	262	6 86 44	16.186
163	2 65 69	12.767	213	4 53 69	14.595	263	6 91 69	16.217
164	2 68 96	12.806	214	4 57 96	14.629	264	6 96 96	16.248
165	2 72 25	12.845	215	4 62 25	14.663	265	7 02 25	16.279
166	2 75 56	12.884	216	4 66 56	14.697	266	7 07 56	16.310
167	2 78 89	12.923	217	4 70 89	14.731	267	7 12 89	16.340
168	2 82 24	12.961	218	4 75 24	14.765	268	7 18 24	16.371
169	2 85 61	13.000	219	4 79 61	14.799	269	7 23 61	16.401
170	2 89 00	13.038	220	4 84 00	14.832	270	7 29 00	16.432
171	2 92 41	13.077	221	4 88 41	14.866	271	7 34 41	16.462
172	2 95 84	13.115	222	4 92 84	14.900	272	7 39 84	16.492
173	2 99 29	13.153	223	4 97 29	14.933	273	7 45 29	16.523
174	3 02 76	13.191	224	5 01 76	14.967	274	7 50 76	16.553
175	3 06 25	13.229	225	5 06 25	15.000	275	7 56 25	16.583
176	3 09 76	13.266	226	5 10 76	15.033	276	7 61 76	16.613
177	3 13 29	13.304	227	5 15 29	15.067	277	7 67 29	16.643
178	3 16 84	13.342	228	5 19 84	15.100	278	7 72 84	16.673
179	3 20 41	13.379	229	5 24 41	15.133	279	7 78 41	16.703
180	3 24 00	13.416	230	5 29 00	15.166	280	7 84 00	16.733
181	3 27 61	13.454	231	5 33 61	15.199	281	7 89 61	16.763
182	3 31 24	13.491	232	5 38 24	15.232	282	7 95 24	16.793
183	3 34 89	13.528	233	5 42 89	15.264	283	8 00 89	16.823
184	3 38 56	13.565	234	5 47 56	15.297	284	8 06 56	16.852
185	3 42 25	13.601	235	5 52 25	15.330	285	8 12 25	16.882
186	3 45 96	13.638	236	5 56 96	15.362	286	8 17 96	16.912
187	3 49 69	13.675	237	5 61 69	15.395	287	8 23 69	16.941
188	3 53 44	13.711	238	5 66 44	15.427	288	8 29 44	16.971
189	3 57 21	13.748	239	5 71 21	15.460	289	8 35 21	17.000
190	3 61 00	13.784	240	5 76 00	15.492	290	8 41 00	17.029
191	3 64 81	13.820	241	5 80 81	15.524	291	8 46 81	17.059
192	3 68 64	13.856	242	5 85 64	15.556	292	8 52 64	17.088
193	3 72 49	13.892	243	5 90 49	15.588	293	8 58 49	17.117
194	3 76 36	13.928	244	5 95 36	15.620	294	8 64 36	17 146
195	3 80 25	13.964	245	6 00 25	15.652	295	8 70 25	17.176
196	3 84 16	14.000	246	6 05 16	15.684	296	8 76 16	17.205
197	3 88 09	14.036	247	6 10 09	15.716	297	8 82 09	17.234
198	3 92 04	14.071	248	6 15 04	15.748	298	8 88 04	17.263
199	3 96 01	14.107	249	6 20 01	15.780	299	8 94 01	17.292
200	4 00 00	14.142	250	6 25 00	15.811	300	9 00 00	17.321

Num.	Square	Sq. Root	Num.	Square	Sq. Root	Num.	Square	Sq. Root
301	9 06 01	17.349	351	12 32 01	18.735	401	16 08 01	20.025
302	9 12 04	17.378	352	12 39 04	18.762	402	16 16 04	20.050
303	9 18 09	17.407	353	12 46 09	18.788	403	16 24 09	20.075
304	9 24 16	17.436	354	12 53 16	18.815	404	16 32 16	20.100
305	9 30 25	17.464	355	12 60 25	18.841	405	16 40 25	20.125
306	9 36 36	17.493	356	12 67 36	18.868	406	16 48 36	20.149
307	9 42 49	17.521	357	12 74 49	18.894	407	16 56 49	20.174
308	9 48 64	17.550	358	12 81 64	18.921	408	16 64 64	20.199
309	9 54 81	17.578	359	12 88 81	18.947	409	16 72 81	20.224
310	9 61 00	17.607	360	12 96 00	18.974	410	16 81 00	20.248
311	9 67 21	17.635	361	13 03 21	19.000	411	16 89 21	20.273
312	9 73 44	17.664	362	13 10 44	19.026	412	16 97 44	20.298
313	9 79 69	17.692	363	13 17 69	19.053	413	17 05 69	20.322
314	9 85 96	17.720	364	13 24 96	19.079	414	17 13 96	20.347
315	9 92 25	17.748	365	13 32 25	19.105	415	17 22 25	20.372
316	9 98 56	17.776	366	13 39 56	19.131	416	17 30 56	20.396
317	10 04 89	17.804	367	13 46 89	19.157	417	17 38 89	20.421
318	10 11 24	17.833	368	13 54 24	19.183	418	17 47 24	20.445
319	10 17 61	17.861	369	13 61 61	19.209	419	17 55 61	20.469
320	10 24 00	17.889	370	13 69 00	19.235	420	17 64 00	20.494
321	10 30 41	17.916	371	13 76 41	19.261	421	17 72 41	20.518
322	10 36 84	17.944	372	13 83 84	19.287	422	17 80 84	20.543
323	10 43 29	17.972	373	13 91 29	19.313	423	17 89 29	20.567
324	10 49 76	18.000	374	13 98 76	19.339	424	17 97 76	20.591
325	10 56 25	18.028	375	14 06 25	19.365	425	18 06 25	20.616
326	10 62 76	18.055	376	14 13 76	19.391	426	18 14 76	20.640
327	10 69 29	18.083	377	14 21 29	19.416	427	18 23 29	20.664
328	10 75 84	18.111	378	14 28 84	19.442	428	18 31 84	20.688
329	10 82 41	18.138	379	14 36 41	19.468	429	18 40 41	20.712
330	10 89 00	18.166	380	14 44 00	19.494	430	18 49 00	20.736
331	10 95 61	18.193	381	14 51 61	19.519	431	18 57 61	20.761
332	11 02 24	18.221	382	14 59 24	19.545	432	18 66 24	20.785
333	11 08 89	18.248	383	14 66 89	19.570	433	18 74 89	20.809
334	11 15 56	18.276	384	14 74 56	19.596	434	18 83 56	20.833
335	11 22 25	18.303	385	14 82 25	19.621	435	18 92 25	20.857
336	11 28 96	18.330	386	14 89 96	19.647	436	19 00 96	20.881
337	11 35 69	18.358	387	14 97 69	19.672	437	19 09 69	20.905
338	11 42 44	18.385	388	15 05 44	19.698	438	19 18 44	20.928
339	11 49 21	18.412	389	15 13 21	19.723	439	19 27 21	20.952
340	11 56 00	18.439	390	15 21 00	19.748	440	19 36 00	20.976
341	11 62 81	18.466	391	15 28 81	19.774	441	19 44 81	21.000
342	11 69 64	18.493	392	15 36 64	19.799	442	19 53 64	21.024
343	11 76 49	18.520	393	15 44 49	19.824	443	19 62 49	21.048
344	11 83 36	18.547	394	15 52 36	19.849	444	19 71 36	21.071
345	11 90 25	18.574	395	15 60 25	19.875	445	19 80 25	21.095
346	11 97 16	18.601	396	15 68 16	19.900	446	19 89 16	21.119
347	12 04 09	18.628	397	15 76 09	19.925	447	19 98 09	21.142
348	12 11 04	18.655	398	15 84 04	19.950	448	20 07 04	21.166
349	12 18 01	18.682	399	15 92 01	19.975	449	20 16 01	21.190
350	12 25 00	18.708	400	16 00 00	20.000	450	20 25 00	21.213

Num.	Square	Sq. Root	Num.	Square	Sq. Root	Num.	Square	Sq. Root
451	20 34 01	21.237	501	25 10 01	22.383	551	30 36 01	23.473
452	20 43 04	21.260	502	25 20 04	22.405	552	30 47 04	23.495
453	20 52 09	21.284	503	25 30 09	22.428	553	30 58 09	23.516
454	20 61 16	21.307	504	25 40 16	22.450	554	30 69 16	23.537
455	20 70 25	21.331	505	25 50 25	22.472	555	30 80 25	23.558
456	20 79 36	21.354	506	25 60 36	22.494	556	30 91 36	23.580
457	20 88 49	21.378	507	25 70 49	22.517	557	31 02 49	23.601
458	20 97 64	21.401	508	25 80 64	22.539	558	31 13 64	23.622
459	21 06 81	21.424	509	25 90 81	22.561	559	31 24 81	23.643
460	21 16 00	21.448	510	26 01 00	22.583	560	31 36 00	23.664
461	21 25 21	21.471	511	26 11 21	22.605	561	31 47 21	23.685
462	21 34 44	21.494	512	26 21 44	22.627	562	31 58 44	23.707
463	21 43 69	21.517	513	26 31 69	22.650	563	31 69 69	23.728
464	21 52 96	21.541	514	26 41 96	22.672	564	31 80 96	23.749
465	21 62 25	21.564	515	26 52 25	22.694	565	31 92 25	23.770
466	21 71 56	21.587	516	26 62 56	22.716	566	32 03 56	23.791
467	21 80 89	21.610	517	26 72 89	22.738	567	32 14 89	23 812
468	21 90 24	21.633	518	26 83 24	22.760	568	32 26 24	23.833
469	21 99 61	21.656	519	26 93 61	22.782	569	32 37 61	23.854
470	22 09 00	21.679	520	27 04 00	22.804	570	32 49 00	23.875
471	22 18 41	21.703	521	27 14 41	22.825	571	32 60 41	23.896
472	22 27 84	21.726	522	27 24 84	22.847	572	32 71 84	23.917
473	22 37 29	21.749	523	27 35 29	22.869	573	32 83 29	23.937
474	22 46 76	21.772	524	27 45 76	22.891	574	32 94 76	23.958
475	22 56 25	21.794	525	27 56 25	22.913	575	33 06 25	23.979
476	22 65 76	21.817	526	27 66 76	22.935	576	33 17 76	24.000
477	22 75 29	21.840	527	27 77 29	22.956	577	33 29 29	24.021
478	22 84 84	21.863	528	27 87 84	22.978	578	33 40 84	24.042
479	22 94 41	21.886	529	27 98 41	23.000	579	33 52 41	24.062
480	23 04 00	21.909	530	28 09 00	23.022	580	33 64 00	24.083
481	23 13 61	21.932	531	28 19 61	23.043	581	33 75 61	24.104
482	23 23 24	21.954	532	28 30 24	23.065	582	33 87 24	24.125
483	23 32 89	21.977	533	28 40 89	23.087	583	33 98 89	24.145
484	23 42 56	22.000	534	28 51 56	23.108	584	34 10 56	24.166
485	23 52 25	22.023	535	28 62 25	23.130	585	34 22 25	24.187
486	23 61 96	22.045	536	28 72 96	23.152	586	34 33 96	24.207
487	23 71 69	22.068	537	28 83 69	23.173	587	34 45 69	24.228
488	23 81 44	22.091	538	28 94 44	23.195	588	34 57 44	24.249
489	23 91 21	22.113	539	29 05 21	23.216	589	34 69 21	24.269
490	24 01 00	22.136	540	29 16 00	23.238	590	34 81 00	24.290
491	24 10 81	22.159	541	29 26 81	23.259	591	34 92 81	24.310
492	24 20 64	22.181	542	29 37 64	23.281	592	35 04 64	24.331
493	24 30 49	22.204	543	29 48 49	23.302	593	35 16 49	24.352
494	24 40 36	22.226	544	29 59 36	23.324	594	35 28 36	24.372
495	24 50 25	22.249	545	29 70 25	23.345	595	35 40 25	24.393
496	24 60 16	22.271	546	29 81 16	23.367	596	35 52 16	24.413
497	24 70 09	22.293	547	29 92 09	23.388	597	35 64 09	24.434
498	24 80 04	22.316	548	30 03 04	23.409	598	35 76 04	24.454
499	24 90 01	22.338	549	30 14 01	23.431	599	35 88 01	24.474
500	25 00 00	22.361	550	30 25 00	23.452	600	36 00 00	24.495

Num.	Square	Sq. Root	Num.	Square	Sq. Root	Num.	Square	Sq. Root
601	36 12 01	24.515	651	42 38 01	25.515	701	49 14 01	26.476
602	36 24 04	24.536	652	42 51 04	25.534	702	49 28 04	26.495
603	36 36 09	24.556	653	42 64 09	25.554	703	49 42 09	26.514
604	36 48 16	24.576	654	42 77 16	25.573	704	49 56 16	26.533
605	36 60 25	24.597	655	42 90 25	25.593	705	49 70 25	26.552
606	36 72 36	24.617	656	43 03 36	25.612	706	49 84 36	26.571
607	36 84 49	24.637	657	43 16 49	25.632	707	49 98 49	26.589
608	36 96 64	24.658	658	43 29 64	25.652	708	50 12 64	26.608
609	37 08 81	24.678	659	43 42 81	25.671	709	50 26 81	26.627
610	37 21 00	24.698	660	43 56 00	25.690	710	50 41 00	26.646
611	37 33 21	24.718	661	43 69 21	25.710	711	50 55 21	26.665
612	37 45 44	24.739	662	43 82 44	25.729	712	50 69 44	26.683
613	37 57 69	24.759	663	43 95 69	25.749	713	50 83 69	26.702
614	37 69 96	24.779	664	44 08 96	25.768	714	50 97 96	26.721
615	37 82 25	24.799	665	44 22 25	25.788	715	51 12 25	26.739
616	37 94 56	24.819	666	44 35 56	25.807	716	51 26 56	26.758
617	38 06 89	24.839	667	44 48 89	25.826	717	51 40 89	26.777
618	38 19 24	24.860	668	44 62 24	25.846	718	51 55 24	26.796
619	38 31 61	24.880	669	44 75 61	25.865	719	51 69 61	26.814
620	38 44 00	24.900	670	44 89 00	25.884	720	51 84 00	26.833
621	38 56 41	24.920	671	45 02 41	25.904	721	51 98 41	26.851
622	38 68 84	24.940	672	45 15 84	25.923	722	52 12 84	26.870
623	38 81 29	24.960	673	45 29 29	25.942	723	52 27 29	26.889
624	38 93 76	24.980	674	45 42 76	25.962	724	52 41 76	26.907
625	39 06 25	25.000	675	45 56 25	25.981	725	52 56 25	26.926
626	39 18 76	25.020	676	45 69 76	26.000	726	52 70 76	26.944
627	39 31 29	25.040	677	45 83 29	26.019	727	52 85 29	26.963
628	39 43 84	25.060	678	45 96 84	26.038	728	52 99 84	26.981
629	39 56 41	25.080	679	46 10 41	26.058	729	53 14 41	27.000
630	39 69 00	25.100	680	46 24 00	26.077	730	53 29 00	27.019
631	39 81 61	25.120	681	46 37 61	26.096	731	53 43 61	27.037
632	39 94 24	25.140	682	46 51 24	26.115	732	53 58 24	27.055
633	40 06 89	25.159	683	46 64 89	26.134	733	53 72 89	27.074
634	40 19 56	25.179	684	46 78 56	26.153	734	53 87 56	27.092
635	40 32 25	25.199	685	46 92 25	26.173	735	54 02 25	27.111
636	40 44 96	25.219	686	47 05 96	26.192	736	54 16 96	27.129
637	40 57 69	25.239	687	47 19 69	26.211	737	54 31 69	27.148
638	40 70 44	25.259	688	47 33 44	26.230	738	54 46 44	27.166
639	40 83 21	25.278	689	47 47 21	26.249	739	54 61 21	27.185
640	40 96 00	25.298	690	47 61 00	26.268	740	54 76 00	27.203
641	41 08 81	25.318	691	47 74 81	26.287	741	54 90 81	27.221
642	41 21 64	25.338	692	47 88 64	26.306	742	55 05 64	27.240
643	41 34 49	25.357	693	48 02 49	26.325	743	55 20 49	27.258
644	41 47 36	25.377	694	48 16 36	26.344	744	55 35 36	27.276
645	41 60 25	25.397	695	48 30 25	26.363	745	55 50 25	27.295
646	41 73 16	25.417	696	48 44 16	26.382	746	55 65 16	27.313
647	41 86 09	25.436	697	48 58 09	26.401	747	55 80 09	27.331
648	41 99 04	25.456	698	48 72 04	26.420	748	55 95 04	27.350
649	42 12 01	25.475	699	48 86 01	26.439	749	56 10 01	27.368
650	42 25 00	25.495	700	49 00 00	26.458	750	56 25 00	27.386

Num.	Square	Sq. Root	Num.	Square	Sq. Root	Num.	Square	Sq. Root
751	56 40 01	27.404	801	64 16 01	28.302	851	72 42 01	29.172
752	56 55 04	27.423	802	64 32 04	28.320	852	72 59 04	29.189
753	56 70 09	27.441	803	64 48 09	28.337	853	72 76 09	29.206
754	56 85 16	27.459	804	64 64 16	28.355	854	72 93 16	29.223
755	57 00 25	27.477	805	64 80 25	28.373	855	73 10 25	29.240
756	57 15 36	27.495	806	64 96 36	28.390	856	73 27 36	29.257
757	57 30 49	27.514	807	65 12 49	28.408	857	73 44 49	29.275
758	57 45 64	27.532	808	65 28 64	28.425	858	73 61 64	29.292
759	57 60 81	27.550	809	65 44 81	28.443	859	73 78 81	29.309
760	57 76 00	27.568	810	65 61 00	28.460	860	73 96 00	29.326
761	57 91 21	27.586	811	65 77 21	28.478	861	74 13 21	29.343
762	58 06 44	27.604	812	65 93 44	28.496	862	74 30 44	29.360
763	58 21 69	27.622	813	66 09 69	28.513	863	74 47 69	29.377
764	58 36 96	27.641	814	66 25 96	28.531	864	74 64 96	29.394
765	58 52 25	27.659	815	66 42 25	28.548	865	74 82 25	29.411
766	58 67 56	27.677	816	66 58 56	28.566	866	74 99 56	29.428
767	58 82 89	27.695	817	66 74 89	28.583	867	75 16 89	29.445
768	58 98 24	27.713	818	66 91 24	28.601	868	75 34 24	29.462
769	59 13 61	27.731	819	67 07 61	28.618	869	75 51 61	29.479
770	59 29 00	27.749	820	67 24 00	28.636	870	75 69 00	29.496
771	59 44 41	27.767	821	67 40 41	28.653	871	75 86 41	29.513
772	59 59 84	27.785	822	67 56 84	28.671	872	76 03 84	29.530
773	59 75 29	27.803	823	67 73 29	28.688	873	76 21 29	29.547
774	59 90 76	27.821	824	67 89 76	28.705	874	76 38 76	29.563
775	60 06 25	27.839	825	68 06 25	28.723	875	76 56 25	29.580
776	60 21 76	27.857	826	68 22 76	28.740	876	76 73 76	29.597
777	60 37 29	27.875	827	68 39 29	28.758	877	76 91 29	29.614
778	60 52 84	27.893	828	68 55 84	28.775	878	77 08 84	29.631
779	60 68 41	27.911	829	68 72 41	28.792	879	77 26 41	29.648
780	60 84 00	27.928	830	68 89 00	28.810	880	77 44 00	29.665
781	60 99 61	27.946	831	69 05 61	28.827	881	77 61 61	29.682
782	61 15 24	27.964	832	69 22 24	28.844	882	77 79 24	29.698
783	61 30 89	27.982	833	69 38 89	28.862	883	77 96 89	29.715
784	61 46 56	28.000	834	69 55 56	28.879	884	78 14 56	29.732
785	61 62 25	28.018	835	69 72 25	28.896	885	78 32 25	29.749
786	61 77 96	28.036	836	69 88 96	28.914	886	78 49 96	29.766
787	61 93 69	28.054	837	70 05 69	28.931	887	78 67 69	29.783
788	62 09 44	28.071	838	70 22 44	28.948	888	78 85 44	29.799
789	62 25 21	28.089	839	70 39 21	28.965	889	79 03 21	29.816
790	62 41 00	28.107	840	70 56 00	28.983	890	79 21 00	29.833
791	62 56 81	28.125	841	70 72 81	29.000	891	79 38 81	29.850
792	62 72 64	28.142	842	70 89 64	29.017	892	79 56 64	29.866
793	62 88 49	28.160	843	71 06 49	29.034	893	79 74 49	29.883
794	63 04 36	28.178	844	71 23 36	29.052	894	79 92 36	29.900
795	63 20 25	28.196	845	71 40 25	29.069	895	80 10 25	29.917
796	63 36 16	28.213	846	71 57 16	29.086	896	80 28 16	29.933
797	63 52 09	28.231	847	71 74 09	29.103	897	80 46 09	29.950
798	63 68 04	28.249	848	71 91 04	29.120	898	80 64 04	29.967
799	63 84 01	28.267	849	72 08 01	29.138	899	80 82 01	29 983
800	64 00 00	28.284	850	72 25 00	29.155	900	81 00 00	30.000

Num.	Square	Sq. Root	Num.	Square	Sq. Root
901	81 18 01	30.017	951	90 44 01	30.838
902	81 36 04	30.033	952	90 63 04	30.854
903	81 54 09	30.050	953	90 82 09	30.871
904	81 72 16	30.067	954	91 01 16	30.887
905	81 90 25	30.083	955	91 20 25	30.903
906	82 08 36	30.100	956	91 39 36	30.919
907	82 26 49	30.116	957	91 58 49	30.935
908	82 44 64	30.133	958	91 77 64	30.952
909	82 62 81	30.150	959	91 96 81	30.968
910	82 81 00	30.166	960	92 16 00	30.984
911	82 99 21	30.183	961	92 35 21	31.000
912	83 17 44	30.199	962	92 54 44	31.016
913	83 35 69	30.216	963	92 73 69	31.032
914	83 53 96	30.232	964	92 92 96	31.048
915	83 72 25	30.249	965	93 12 25	31.064
916	83 90 56	30.265	966	93 31 56	31.081
917	84 08 89	30.282	967	93 50 89	31.097
918	84 27 24	30.299	968	93 70 24	31.113
919	84 45 61	30.315	969	93 89 61	31.129
920	84 64 00	30.332	970	94 09 00	31.145
921	84 82 41	30.348	971	94 28 41	31.161
922	85 00 84	30.364	972	94 47 84	31.177
923	85 19 29	30.381	973	94 67 29	31.193
924	85 37 76	30.397	974	94 86 76	31.209
925	85 56 25	30.414	975	95 06 25	31.225
926	85 74 76	30.430	976	95 25 76	31.241
927	85 93 29	30.447	977	95 45 29	31.257
928	86 11 84	30.463	978	95 64 84	31.273
929	86 30 41	30.480	979	95 84 41	31.289
930	86 49 00	30.496	980	96 04 00	31.305
931	86 67 61	30.512	981	96 23 61	31.321
932	86 86 24	30.529	982	96 43 24	31.337
933	87 04 89	30.545	983	96 62 89	31.353
934	87 23 56	30.561	984	96 82 56	31.369
935	87 42 25	30.578	985	97 02 25	31.385
936	87 60 96	30.594	986	97 21 96	31.401
937	87 79 69	30.610	987	97 41 69	31.417
938	87 98 44	30.627	988	97 61 44	31.432
939	88 17 21	30.643	989	97 81 21	31.448
940	88 36 00	30.659	990	98 01 00	31.464
941	88 54 81	30.676	991	98 20 81	31.480
942	88 73 64	30.692	992	98 40 64	31.496
943	88 92 49	30.708	993	98 60 49	31.512
944	89 11 36	30.725	994	98 80 36	31.528
945	89 30 25	30.741	995	99 00 25	31.544
946	89 49 16	30.757	996	99 20 16	31.559
947	89 68 09	30.773	997	99 40 09	31.575
948	89 87 04	30.790	998	99 60 04	31.591
949	90 06 01	30.806	999	99 80 01	31.607
950	90 25 00	30.822	1000	100 0000	31.623

TABLE OF TANGENTS, COSINES, AND SINES

Angle	Tangent $\left(\frac{opp.}{adj.}\right)$	Cosine $\left(\frac{adj.}{hyp.}\right)$	Sine $\left(\frac{opp.}{hyp.}\right)$	Angle	Tangent $\left(\frac{opp.}{adj.}\right)$	Cosine $\left(\frac{adj.}{hyp.}\right)$	Sine $\left(\frac{opp.}{hyp.}\right)$
0°	.000	1.000	.000	45°	1.000	.707	.707
1	.017	1.000	.017	46	1.036	.695	.719
2	.035	.999	.035	47	1.072	.682	.731
3	.052	.999	.052	48	1.111	.669	.743
4	.070	.998	.070	49	1.150	.656	.755
5	.087	.996	.087	50	1.192	.643	.766
6	.105	.995	.105	51	1.235	.629	.777
7	.123	.993	.122	52	1.280	.616	.788
8	.141	.990	.139	53	1.327	.602	.799
9	.158	.988	.156	54	1.376	.588	.809
10	.176	.985	.174	55	1.428	.574	.819
11	.194	.982	.191	56	1.483	.559	.829
12	.213	.978	.208	57	1.540	.545	.839
13	.231	.974	.225	58	1.600	.530	.848
14	.249	.970	.242	59	1.664	.515	.857
15	.268	.966	.259	60	1.732	.500	.866
16	.287	.961	.276	61	1.804	.485	.875
17	.306	.956	.292	62	1.881	.469	.883
18	.325	.951	.309	63	1.963	.454	.891
19	.344	.946	.326	64	2.050	.438	.899
20	.364	.940	.342	65	2.145	.423	.906
21	.384	.934	.358	66	2.246	.407	.914
22	.404	.927	.375	67	2.356	.391	.921
23	.424	.921	.391	68	2.475	.375	.927
24	.445	.914	.407	69	2.605	.358	.934
25	.466	.906	.423	70	2.747	.342	.940
26	.488	.899	.438	71	2.904	.326	.946
27	.510	.891	.454	72	3.078	.309	.951
28	.532	.883	.469	73	3.271	.292	.956
29	.554	.875	.485	74	3.487	.276	.961
30	.577	.866	.500	75	3.732	.259	.966
31	.601	.857	.515	76	4.011	.242	.970
32	.625	.848	.530	77	4.331	.225	.974
33	.649	.839	.545	78	4.705	.208	.978
34	.675	.829	.559	79	5.145	.191	.982
35	.700	.819	.574	80	5.671	.174	.985
36	.727	.809	.588	81	6.314	.156	.988
37	.754	.799	.602	82	7.115	.139	.990
38	.781	.788	.616	83	8.144	.122	.993
39	.810	.777	.629	84	9.514	.105	.995
40	.839	.766	.643	85	11.430	.087	.996
41	.869	.755	.656	86	14.301	.070	.998
42	.900	.743	.669	87	19.081	.052	.999
43	.933	.731	.682	88	28.636	.035	.999
44	.966	.719	.695	89	57,290	.017	1.000
45	1.000	.707	.707	90		.000	1.000

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No. 27. *Pilots' Airplane Manual*
No. 28. *Pilots' Powerplant Manual*
No. 30. *Ground Instructor's Manual*

The Greek Alphabet

α	alpha	ι	iota	ρ	rho
β	beta	κ	kappa	σ	sigma
γ	gamma	λ	lambda	τ	tau
δ	delta	μ	mu	υ	upsilon
ϵ	epsilon	ν	nu	ϕ	phi
ζ	zeta	ξ	xi	χ	chi
η	eta	o	omicron	ψ	psi
θ	theta	π	pi	ω	omega

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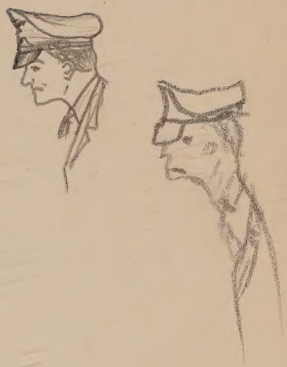

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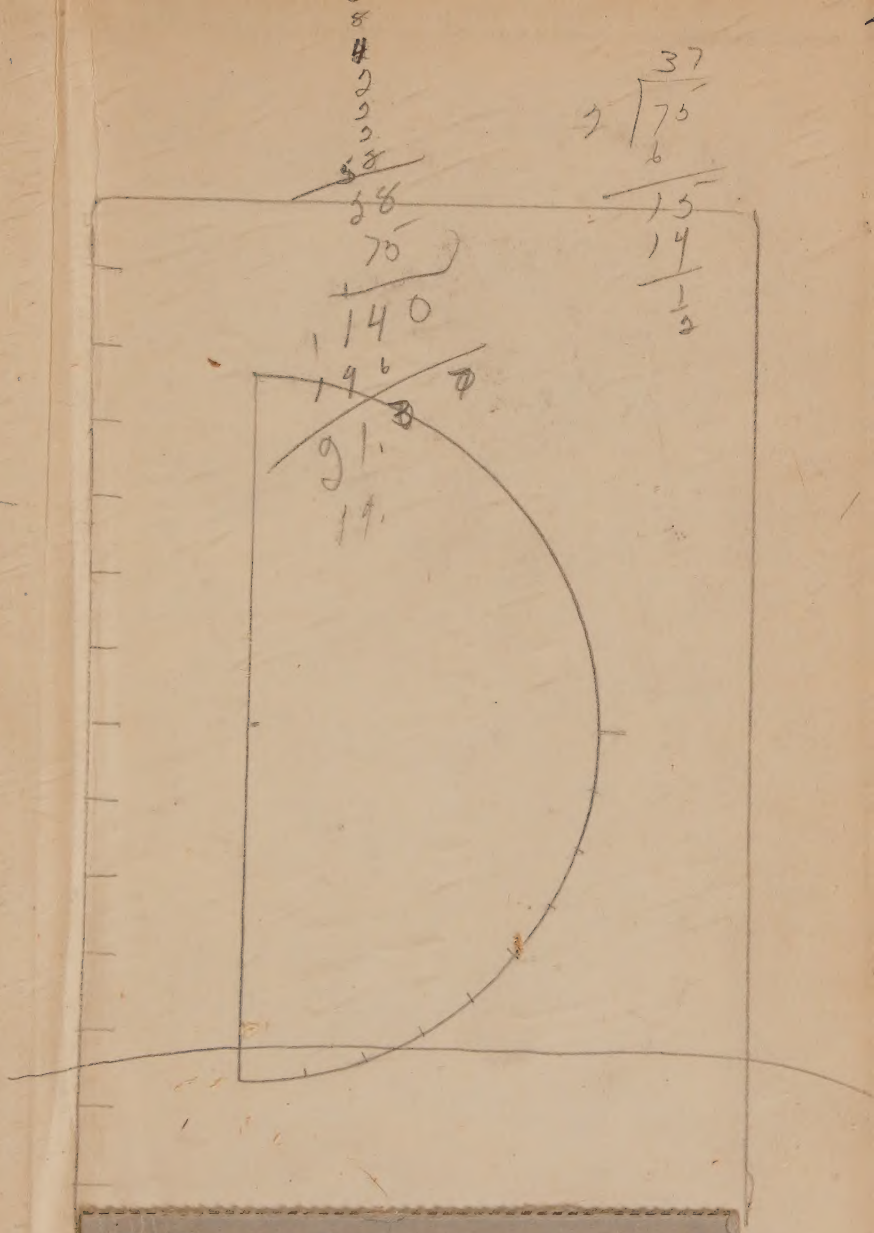

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